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REVIEW

Badenian evolution of the Central Paratethys Sea: paleogeography, climate and eustatic sea-level changes

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Abstract: The Miocene Central Paratethys Sea covered wide areas of the Pannonian Basin System, bordered by the mountain chains of the Alps, Carpathians and Dinarides. The epicontinental sea spread not only in the back-arc basin area, but flooded even the Alpine-Carpathian Foredeep, situated along the front of gradually uplifting mountains. The Early Badenian (early Langhian) transgressions from the Mediterranean toward the Central Paratethys realm, via Slovenia and northern Croatia (Transtethyan Trench Corridor or Trans Dinaride Corridor) flooded the Pannonian Basin and continued along straits in the Carpathian Chain into the Carpathian Foredeep. The isolation of eastern parts of the Central Paratethys at the end of this period (late Langhian) resulted in the "Middle Badenian" salinity crisis. Thick evaporite sediments, above all halite and gypsum were deposited in the Transcarpathian Basin, Transylvanian Basin and Carpathian Foredeep. During the Late Badenian (early Serravallian), the latest full marine flooding covered the whole back-arc basin and a great part of the foredeep. The main problem is to create a model of sea connections during that time, because some authors consider the western Transtethyan Trench Corridor (Trans Dinaride Corridor) closed and there is no evidence to prove a supposed strait towards the Eastern Mediterranean. A proposed possibility is a connection towards the Konkian Sea of the Eastern Paratethys. The Badenian climate of the Central Paratethys realm can be characterized as fairly uniform, reflecting the stable subtropical conditions of the Miocene Climatic Optimum. No considerable changes in terrestrial ecosystems were documented. Nevertheless, evolution of steep landscape associated with rapid uplift of the East Alpine and Western Carpathian mountain chains (including high stratovolcanoes) caused development of vertical zonation of dry land and consequently close occurrence of different vegetation zones in a relatively small distance during this time. In the Central Paratethys Sea a slight N-S climatic gradient seems to be expressed already from the Early Badenian, but a biogeographic differentiation between basins in the North and South starts to become more prominent first during the Late Badenian, when a moderate cooling of the seawater can also be documented. The Late Badenian sea-level highstand coincides with the appearance of stress factors such as stratification of the water column and hypoxic conditions at the basin bottom in the whole area. Taking into account all bioevents and changes of paleogeography in the Central Paratethys realm, we can very roughly correlate the Early (and "Middle") Badenian with the eustatic sea-level changes of TB 2.3, TB 2.4 or Bur5/Lan1, Lan2/Ser1 and the Late Badenian with TB 2.5 or Ser2 cycles (sensu Haq et al. 1988; Hardenbol et al. 1998). Generally, we can assign the Early Badenian transgressions to be controlled by both, tectonics (induced mainly by back-arc basin rifting) and eustacy, followed by forced regression. The Late Badenian transgression and regression were dominantly controlled by sea-level changes inside the Central Paratethys realm.

Key words: Miocene, Badenian, Central Paratethys, paleogeography, tectonics, climate, sequence stratigraphy.

Introduction

As a contribution to the European Science Foundation Project — Environments and Ecosystem Dynamics of the Eurasian Neogene (2000–2005), the Central Paratethys realm Karpatian paleogeography, tectonics and eustatic changes (in the time interval 17.2–16.3 Ma, sensu Harzhauser & Piller 2007) were revised and published in a monograph dealing with the Karpatian stage (Brzobohatý, Cicha, Kováč & Rögl (Eds.) 2003). The article of Kováč et al. (2003) comprises all-important data about geodynamic settings and geology of the Alpine-Carpathian-Pannonian region, introduction to the methodology used in the preparation of a palinspastic model of paleogeography, as well as basic terms preferred in regional stratigraphy of the Central Paratethys. The results of the following research, Badenian paleogeography, tectonics and sea-level changes in the Central Paratethys are presented below.

Chronological position of the Badenian stage

The term **Badenian** was introduced and defined as a chronostratigraphic stage by Papp & Cicha in 1968 and was subdivided into three substages: Moravian, Wielician and Kosovian (comp. Papp et al. 1978, p. 51–52). These subdivisions based on planktonic foraminifers were subsequently widely adopted but the previous zonation based on benthic foraminifers proposed by Grill (1941, 1943) for the Vienna Basin also remained in use. On the contrary, it is the most widely used scheme today, especially for shallow-water deposits where planktonic organisms are extremely poorly represented. The zonation consists of a vertical succession of benthic foraminiferal assemblages — based zones namely Lower and Upper Lagenidae, *Spiroplectammina carinata* (= *Spirorutilus carinatus*) and *Bulimina-Bolivina,* impoverished or *Rotalia* Zones. The Grill zonation was revised by Papp & Turnovsky (1953) and based on uvigerinid evolutionary lineages. Also in this paper Grill's zones are regarded as the equivalent of particular substages in spite of that the relationship between benthic and planktonic zonation may be defined only imperfectly (Table 1, *the latest Miocene chronostratigraphy and biostratigraphy can be found in the paper of Harzhauser & Piller 2007*).

The Central Paratethys regional stage Badenian, corresponding to the regional stages late Tarkhanian, Chokrakian, Karaganian, and Konkian distinguished in the Eastern Paratethys (Nevesskaya et al. 1987; Studencka et al. 1998; Meulenkamp & Sissingh 2000) is an equivalent of the Mediterranean standard stages Langhian and early Serravallian.

From the biostratigraphical point of view the Badenian can be clearly subdivided only into the Early and Late Badenian (Table 1), which is in contradiction to the used trimerous subdivision into the Early, Middle and Late Badenian (e.g. Rögl 1998) and does not correspond to a division into "Lower and Upper Tortonian" in the sense of the Vienna Basin stratigraphy of the fifties and sixties of the preceeding century (e.g. Buday 1955).

Rögl (1998) like other authors divided the Badenian into **Early, Middle** and **Late Badenian**. The lower boundary of the Early Badenian was placed at 16.4 Ma, the boundary for the Early/Middle Badenian at approximately 15 Ma, the Middle/Late Badenian boundary at 14 Ma and 13 Ma was used as the Late Badenian/Sarmatian boundary. However, the correct correlation between the Badenian sub-stages defined by benthic organisms and the planktic world-zonations is still missing. The widely used zonation of Grill (1941, 1943) based on benthic foraminifers is quite consistent in itself, however, at the same time, it is strongly facies-dependent and poorly correlated with the planktonic zonations.

The base of the Badenian (**Early Badenian** lower boundary) is marked by the FAD of the genus *Praeorbulina* positioned in the late calcareous nannoplankton NN4 Zone (Rögl et al. 2002). The base of the Badenian is isochronous with the base of the Langhian and the "*Praeorbulina* datum" which has been recently re-calibrated from 16.4 Ma to 16.303 Ma, base of Chron C5Cn.1r (EEDEN time scale, Harzhauser & Piller 2007). The implied age of 15.97 Ma (Gradstein et al. 2004), instead of datum 16.4 Ma (sensu Berggren et al. 1995) is not based on any new results but was drawn without comments at the reversal boundary on top of Chron C5Br. In the text of Lourens et al. (2004) the *Praeorbulina* datum is still in use to define the base of the Langhian.

However, this biostratigraphically well-defined stage boundary is recognizable only in limited areas of the Central Paratethys (Kováč et al. 1999; Kováč et al. 2001; Rögl et al. 2002). Instead, the lowermost Badenian strata which can be recognized almost everywhere in the Central Paratethys realm contain planktonic foraminiferal assemblages in which the genus *Praeorbulina* is associated with the genus *Orbulina* in the calcareous nannoplankton Zone NN5 (Berggren et al. 1995; Fornaciari & Rio 1996).

The NN5 Zone was defined by Berggren et al. (1995) by the presence of *Sphenolithus heteromorphus* Deflandre and by the absence of *Helicosphaera ampliaperta* (Bramlette et Wilcoxon) Bukry. Recently, the LAD of *H. ampliaperta* was correlated with an age of 14.91 Ma, and that of *S. heteromorphus* was astronomically calibrated with an age of 13.65 (Lourens et al. 2004), marking the Langhian/Serravallian boundary (Sprovieri et al. 2002).

The **Late Badenian** lower boundary is marked by the first appearance of the warm-water planktonic foraminifer *Velapertina indigena* (Łuczkowska) in marine deposits of the Central Paratethys region (Łuczkowska 1971; Papp et al. 1978; Rögl 1998). It is somewhat younger than the boundary between NN5 and NN6 Zones of calcareous nannoplankton (Martini 1971). In addition, the radiolarian horizon best documented through the Carpathian Foredeep, Transcarpathian and Transylvanian Basins (Dumitrică 1978; Barwicz-Piskorz 1981, 1999; Rögl 1998) shows a high potential for regional correlations. The radiolarian assemblage derived in this widespread horizon belongs to the *Dorcadospyris alata* Zone in the zonal scheme of Sanfilippo et al. (1985) for the Mediterranean and corresponds to the basal part of the NN6 Zone of calcareous nannoplankton (sensu Martini 1971).

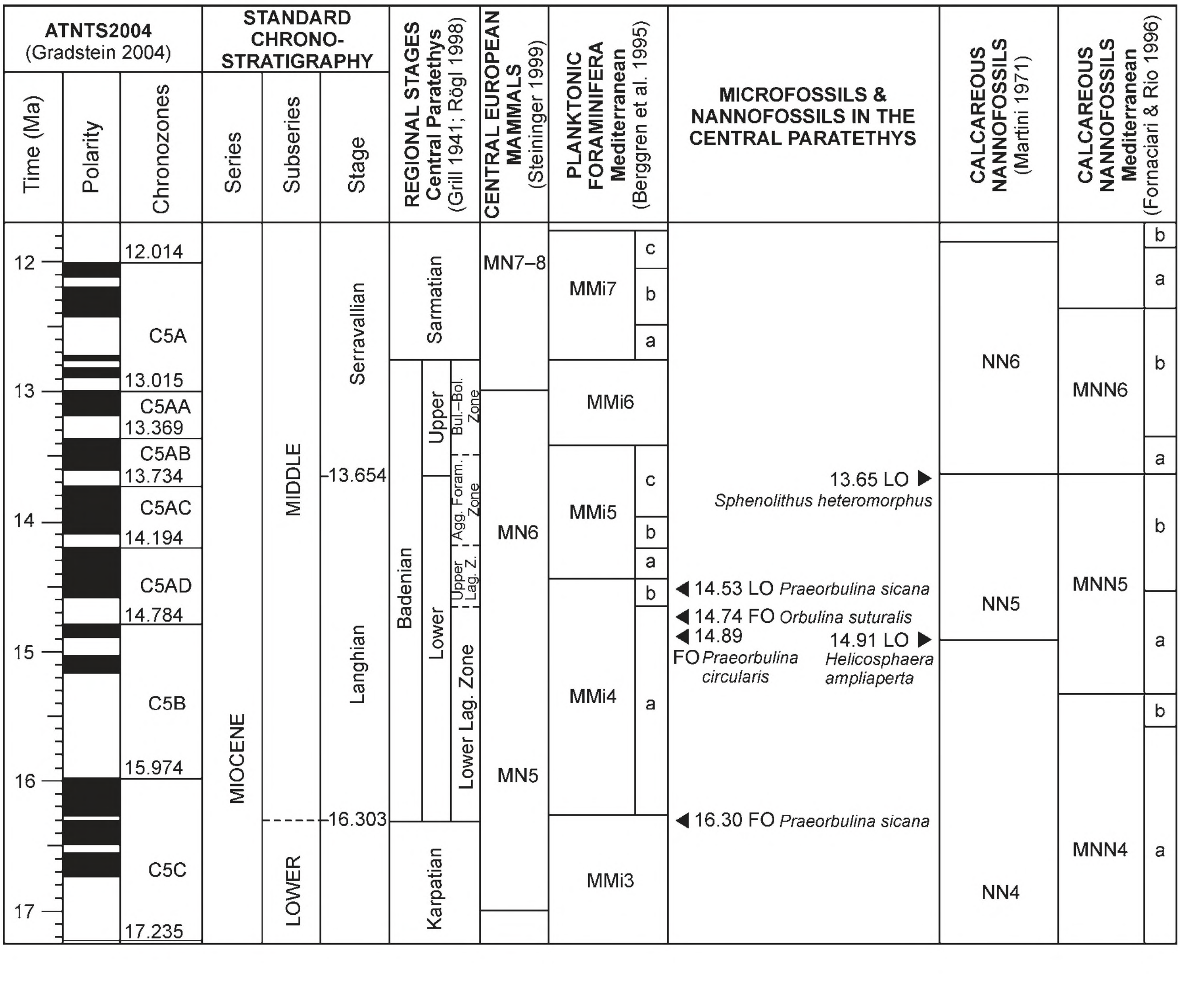
The time span of the Late Badenian (~13.6–12.7 Ma) can only be estimated. It appears that it is approximately coeval to the upper part of the M7 *Globorotalia peripheroacuta* Lineage Zone of Berggren et al. (1995) with estimated age 14.8–12.7 Ma and the lower part of the *Discoaster exilis* Zone (NN6 Zone of calcareous nanoplankton, sensu Martini 1971) with estimated age according to Berggren et al. (1995): 13.6–11.8 Ma. The planktonic foraminiferal standard biozonation, both of Blow (1969) and Berggren et al. (1995), can only partly be applied to Paratethys stratigraphy, due to the absence of index taxa in this peripheral epicontinental sea.

The upper boundary of the Badenian should be defined by the first appearance of endemic Sarmatian faunas, such as the FAD of *Anomalinoides dividens* (Łuczkowska 1964, 1971; Filipescu 2004b). The revised boundary age is based on astronomical cycles and correlation with the isotope event MSI-3 at 12.7 Ma (Harzhauser & Piller 2004).

Geodynamic development of the Alpine-Carpathian-Pannonian region and paleogeography of the Central Paratethys Sea during the Badenian

The **Central Paratethys Sea** extended over a large area between the Eastern Alps and Dinarides in the West and Southwest and Carpathians in the North, East and Southeast. Its Badenian paleogeography depended strongly on the geodynamic development of the Alpine-Carpathian

Table 1: Biostratigraphy of the Badenian sediments in the Central Paratethys basins. *Because of the frequent use of the Calcareous Nannoplankton Zones of Martini (1971) in the Paratethys literature they have been recalibrated according to Gradstein et al. (2004).*



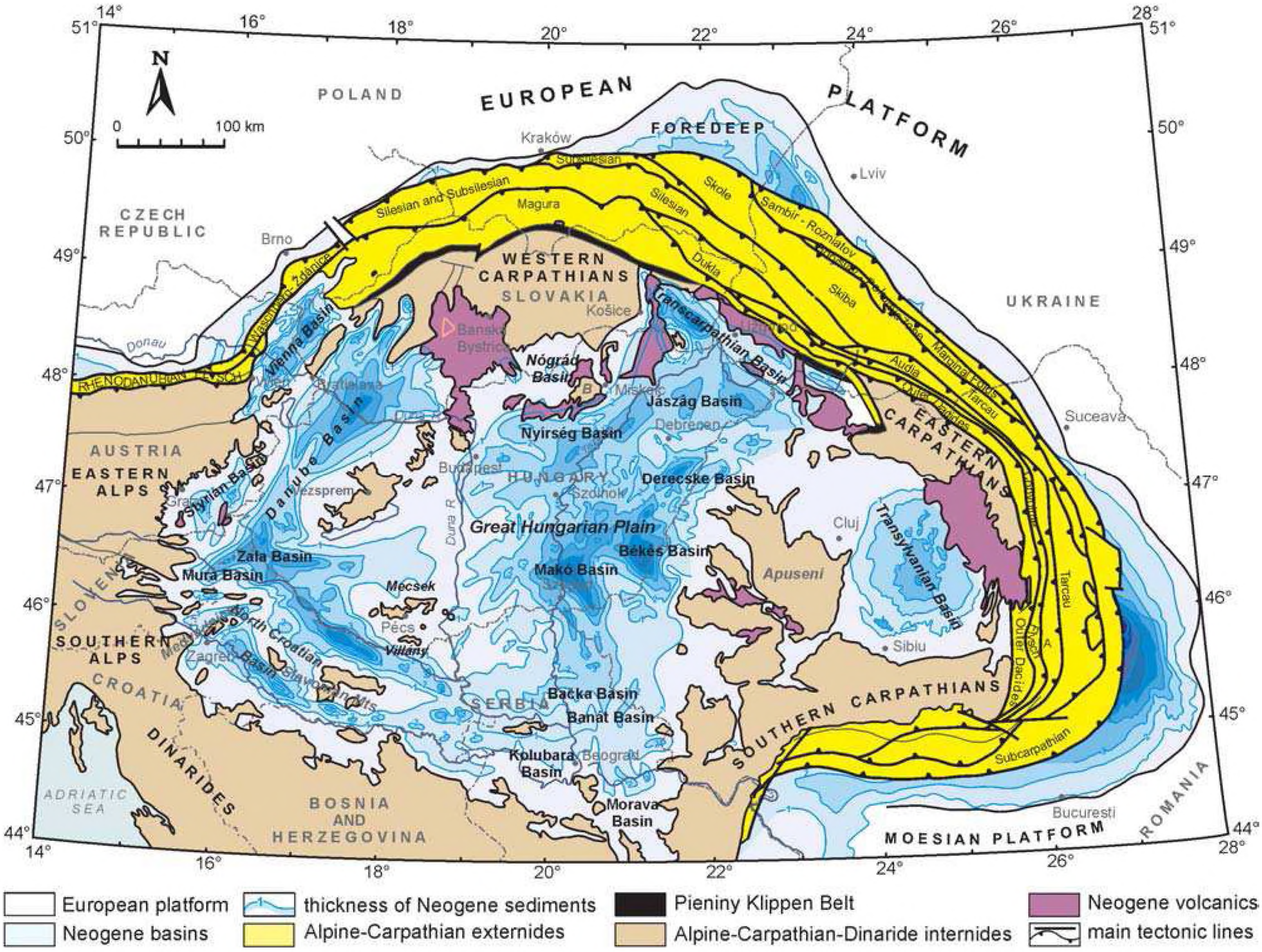


Fig. 1. Alpine-Carpathian-Pannonian-Dinaride domain.

mountain chains and development of basins within the Pannonian Basin System and Carpathian Foredeep (Fig. 1). Changes in the structural pattern (tectonics) of the area were highly influenced by subduction in front of the orogene, as well as by the back-arc extension. The different driving forces, the changing geometry of the external Carpathian thrust system might have led to a spatially and temporally variable stress field (Nemčok et al. 1998; Fodor et al. 1999; Kováč 2000) and induced different types of magmatism; extension-dominated in the western and subduction-related in the eastern Pannonian-Carpathian realm (Pécskay et al. 1995; Harangi 2001; Konečný et al. 2002).

The presented palinspastic model of the **Badenian paleogeography of the Alpine-Carpathian-Pannonian domain** (Figs. 2, 4) takes into consideration the position of an active subduction zone in front of the moving lithospheric fragments–microplates, at that time (Balla 1984; Csontos et al. 1992; Kováč M. et al. 1994, 1998; Kováč 2000; Konečný et al. 2002). The configuration of the Alcapa (Alpine-Carpathian-Pannonian) and Tisza–Dacia microplates can be more or less characterized by their "final" juxtaposition along the Mid-Hungarian Zone (Csontos et al. 1992; Csontos 1995; Csontos & Nagymarosy 1998), after major rotational events (Márton 2001). However, some elements of this fault system were still active during and after the Badenian and produced some short-extent horizontal movements (for example the Balaton Line).

Subduction of the European Platform margin (Fig. 2), involving a slab comprising the basement of Outer Carpathian basins/units, namely the basement of the Krosno–Menilite and Outer Moldavides zones, resulted in compression tectonics, which was bound only to a narrow belt near the collision zone. The compression led to folding and nappe thrusting in the Carpathian accretionary wedge. This "tectonic phase" is traditionally named the "Styrian phase" or the "intra-Badenian orogenetic movements" (Săndulescu 1988; Oszczypko & Ślączka 1989; Oszczypko 1997, 1998; Oszczypko & Lucińska-Anczkiewicz 2001; Oszczypko et al. 2006).

The **Pannonian Basin System** (Fig. 2) marks out syn-rift faulting and related subsidence of separate depocentres, whose development was controlled by various geodynamic mechanisms (Meulenkamp et al. 1996; Kováč et al. 1997a; Kováč 2000; Pavelić 2001; Tomljenović & Csontos 2001; Lučić et al. 2001; Konečný et al. 2002; Saftić et al. 2003). The basin system depocentres represent at

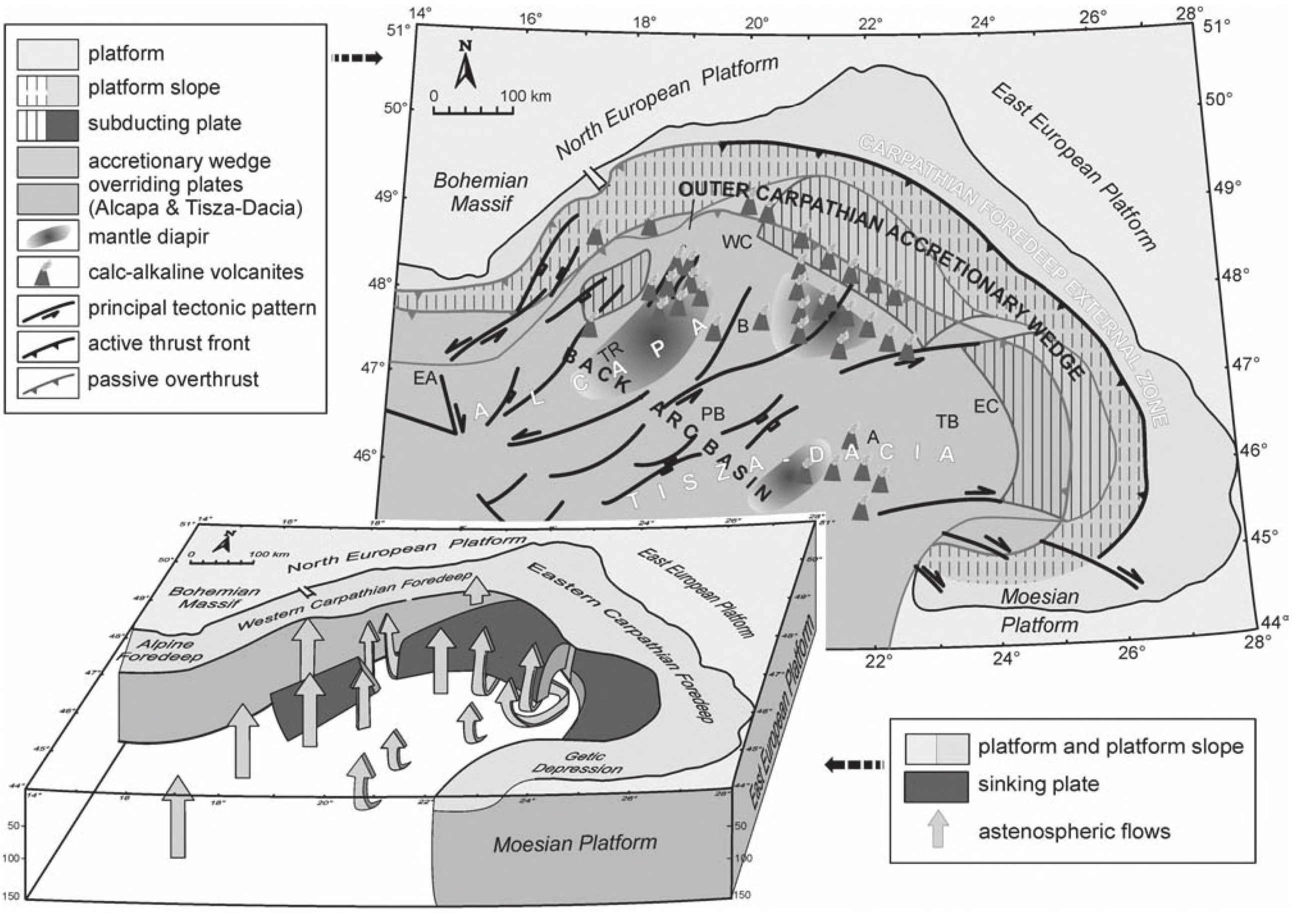


Fig. 2. Block-diagram demonstrating geodynamical factors, which influenced development of the Carpathian Chain and Pannonian back-arc basin system during the Late Badenian (**EA** — Eastern Alps, **TR** — Transdanubian Ridge, **WC** — Western Carpathians, **B** — Bükk Mts, **EC** — Eastern Carpathians, **A** — Apuseni Mts, **TB** — Transylvanian Basin, **PB** — Pannonian Basin).

present mainly individual basins of the back-arc basin domain, such as the Danube, Styrian, Zala, Mura, North Croatian (Drava and Sava Depressions), Transcarpathian, several Great Hungarian Plain basins, including the Vienna and Transylvanian Basins as well.

In the **western part** of the back-arc basin the main driving force of the Badenian basin formation was asthenospheric mantle uplift, following subduction in front of the Alpine-Carpathian Chain. In the **central and eastern part** of the back-arc basin the subsidence was more directly linked to subduction pull. The pull effect of the down-going plate caused stretching of the overriding microplates predominantly in the NE-SW and E-W directions (Royden 1993a,b; Csontos 1995; Fodor et al. 1999; Sperner et al. 2002, 2004; Horváth et al. 2006). Therefore, NW-SE extension dominated during basin formation in the northwestern part of the Pannonian realm, and was associated with acid and calc-alkaline volcanism (Pécskay et al. 1995). In the southwestern part of the Pannonian realm the asthenospheric mantle uplift led to the formation of elongated and deep half-grabens influenced by NNE-SSW extension, followed by E-W extension (Pavelić 2001). Behind the active collision zone of the Carpathian Chain, in the central and eastern part of the Pannonian Basin System the subsidence was influenced mostly by NE-SW to E-W oriented extension.

The Outer Carpathian accretionary wedge and Carpathian Foredeep

During the Badenian, formation of the **Outer Carpathian accretionary wedge** was in progress along the whole front of the Western and Eastern Carpathians. The stacking of thrust sheets was accompanied by compression oriented perpendicularly to the orogene axis (Figs. 1, 3a,b), generally towards the northeast–east in the Western and Eastern Carpathians (Kováč et al. 1998). The westernmost part of the Carpathians formed an exception and is considered inactive since the Middle Badenian. However, ductile deformations of the Lower Badenian sediments (one-meter to about ten-meter long folds) were newly documented near the front of the nappes in the Moravian Gate at Bělotín and Hranice (Havíř & Otava 2004). In that western part the Late Badenian paleostress field was marked by (W) NW-(E) SE extension in the Vienna Basin (Nemčok 1991; Nemčok et al. 1993; Fodor 1995). The Eastern and Southern Carpathians are characterized by a paleostress

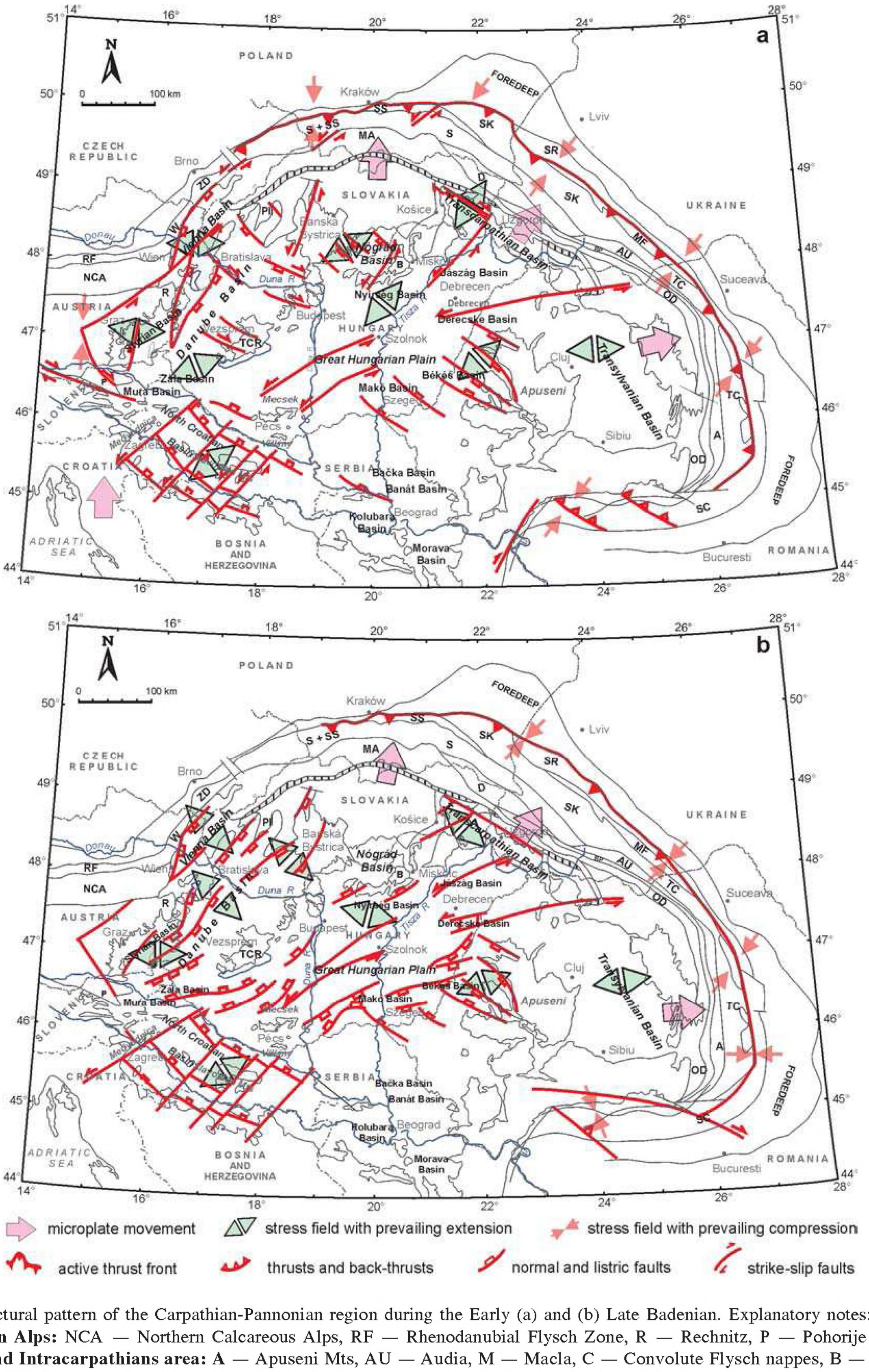


Fig. 3. Structural pattern of the Carpathian-Pannonian region during the Early (a) and (b) Late Badenian. Explanatory notes: **Southern and Eastern Alps:** NCA — Northern Calcareous Alps, RF — Rhenodanubial Flysch Zone, R — Rechnitz, P — Pohorije Mts. **Carpathians and Intracarpathians area:** A — Apuseni Mts, AU — Audia, M — Macla, C — Convolute Flysch nappes, B — Bükk Mts, BP — Borislav-Pokuty Nappe, D — Dukla Nappe, MA — Magura Nappe, MF — Marginal Folds Nappe, MK — Malé Karpaty Mts, PI — Považský Inovec Mts, OD — Outer Dacides, PKB — Pieniny Klippen Belt, S — Silesian Nappe, SC — Subcarpathian Nappe, SK — Skole, Skiba Nappe, SR — Sambor-Rozniatov Nappe, SS — Subsilesian Nappe, TC — Tarcău Nappe, TCR — Transdanubian Range, ZD — Ždánice Nappe, W — Waschberg Zone.

field with NE–SW oriented main compression, which later in the Southern Carpathians changed to compression oriented NW-SE (Maţenco 1997).

Active thrusting of the Outer Carpathians resulted in movement of nappes, the Subsilesian and Silesian Units (from bottom to top) in the northern segment of the Western Carpathians, while the Skole-Skiba and Tarcău Nappes thrusted over the Borislav-Pokuty and Marginal Fold Units in the northeastern and in the Eastern Carpathians (Săndulescu 1988). Uplift of the accretionary wedge was not continuous along the whole Carpathian loop. The northern part started to emerge, but the eastern part remained submerged below the sea level, as documented, for example, by the presence of the Lower Badenian sediments on the Tarcău Nappe (Micu 1990).

The **Carpathian Foredeep** development was characterized by a migration of depocentres generally from the West towards the East during the Badenian (Meulenkamp et al. 1996). The Early Badenian foredeep in Moravia (westernmost part of the Carpathian Foredeep) originated as a relatively narrow flexural basin (Central Depression; e.g. Eliáš 1999), which could be connected with the detachment process of the platform lithosphere after the end of subduction of its passive margin (Tomek 1999). The base of deposits is not coeval; the thickness of the sedimentary fill varies greatly from 400 m in the South to 1100 m in the North. Sedimentation started with continental breccias and sands followed by shallow marine gravels and sands at first of delta origin. In deeper parts of the foredeep calcareous clays were deposited. The loading of nappes caused subsidence, above all in the West and was followed by transgression over the adjacent margin of the Bohemian Massif. Deep-water calcareous clays with sporadic algal and bryozoan limestones and sandstones in shallows or elevated places were deposited (Doláková et al. 2005).

The sediments of the Lower Badenian in the westernmost part of the Carpathian Foredeep are stratigraphically characterized by *Praeorbulina glomerosa circularis* (Blow) and *Orbulina suturalis* Brönnimann. Nannoplankton with *Helicosphaera waltrans* Theodoridis indicates the calcareous nannoplankton NN5 Zone (Švábenická 2002; Ćorić & Švábenická 2004). However, the uppermost NN4 Zone is possible in the oldest sediments (Grund Fm) of the Lower Badenian in the Lower Austrian Alpine Molasse Basin (Ćorić & Rögl 2004). In the Moravian part of the Foredeep (Czech Republic) the sedimentation already ended after the Early Badenian (Kováč et al. 1989).

The "Middle Badenian" evaporite event, preceding the Late Badenian transgression, can be followed from the North towards East and Southeast along the whole foredeep. It is dated to the boundary of the calcareous nannoplankton Zones NN5 and NN6, or to the base of NN6 (sensu Martini 1971). During the evaporite event mostly sulphate facies were deposited in shallow littoral parts of the foredeep, while chloride-sulphate facies developed in the deepest part of the basin, in front of the accretion wedge of the Outer Carpathians (Oszczypko & Ślączka 1989; Oszczypko 1997; Petrichenko et al. 1997; Andreyeva-Grigorovich et al. 1999, 2003; Oszczypko et al. 2006; Bąbel 2004, 2005). The "Middle Miocene" evaporite deposition is known not only from the Carpathian Foredeep, but also from the neighbouring intra-Carpathian basins, such as the Transcarpathian Basin in the North and Transylvanian Basin in the South (Kováč et al. 1998; Krezsek & Bally 2006).

After the "Middle Badenian" salinity crisis, telescopic shortening of the Outer Western Carpathians accretionary wedge took place and the active orogene front moved 20–30 km towards the northeast (Oszczypko 1997; Andreyeva-Grigorovich et al. 1999, 2003). The Late Badenian Carpathian Foredeep depocentres with maximal subsidence developed along the Western and Eastern Carpathians junction, mirroring not only the weight of the Carpathian thrust stack (Oszczypko 1997), but also the deep subsurface load of the down-going plate (Krzywiec 1997; Krzywiec & Jochym 1997) and its flexural deformation (Zoetemeier et al. 1999). The thickness of the Upper Badenian sedimentary sequences in this region reaches 2000–2500 m (Meulenkamp et al. 1996; Kováč et al. 1996; Andreyeva-Grigorovich et al. 1997). The Upper Badenian sediments in addition to nearshore and offshore molasse deposits also consist of a large amount of turbidity current deposits, whose sources of material were deltas prograding from the uplifted parts of the accretionary wedge of the Outer Carpathians towards the foredeep (Oszczypko 1996). Apart from development of the foredeep depocentres a wide area of the Carpathian foreland was also flooded, and the shoreline shifted towards the NE (Fig. 4). The sea also flooded marginal parts of the Outer Carpathian accretionary wedge, as well as the northern part of the Magura Nappe (offshore facies in the Nowy Sącz Basin, see Oszczypko et al. 2006).

For the understanding of the Badenian paleogeographical setting of the **Eastern Carpathians** we should consider that deep-sea, offshore Upper Badenian deposits (radiolarian shales and the pteropode-bearing *Spiratella* marls) are folded into the Tarcău and Marginal Folds nappes. It means practically, that some parts of the Moldavides were still in a sub-marine position during the Late Badenian (see also Dumitrică et al. 1975; Popescu 1979; Săndulescu et al. 1981). In fact, the Carpathians did not represent an important sedimentary source before the Late Sarmatian either for the foreland (foredeep) or for the back-arc basin area (Krézsek & Bally 2006). During the Middle Miocene (Late Badenian–Middle Sarmatian) at least, the present-day Carpathian bend was submerged, while the northern part of the Eastern Carpathians and the western part of the Southern Carpathians may have formed a rather low elevated ridge.

In the central and southern part of the Eastern Carpathian Foredeep, the thickness of Badenian sediments is very variable and depends on the size of the platform flexure. It ranges between 500–1000 m in the North and about 1000–1500 m in the southern part of the foredeep (Săndulescu et al. 1981; Dicea 1995, 1996). The maturity of sandstones and relatively great amount of clays and silt clays support the absence of an "active" relief along the basin margins (Micu 1990). The thickness of the Badenian deposits covering the Moesian Platform reaches its maximum (about 500–1000 m) in front of the Southern Carpathians (Dicea 1996; Tari et al. 1997).

The Pannonian Basin System (including Vienna and Transylvanian Basins)

During the Badenian the greatest part of the "Pannonian back-arc basin area" subsided. However, a narrow belt North of the Mid-Hungarian Zone was represented by more or less uplifted areas. Those were the Transdanubian Range Mts (partly), Bükk Mts, Central and Inner Western Carpathians (partly). South of the Mid-Hungarian Zone an archipelago of islands occurred on the Tisza-Dacia microplate, the Apuseni Mts represented the largest island in the Southeast. The Pannonian Basin System in the Late Badenian was surrounded by the uplifting Eastern Alps in the West, Western Carpathians in the North (partly), by the islands of the Eastern Carpathians to the East and the Southern Carpathians and Dinarides in the South and Southwest (Figs. 1, 4).

In the hinterland of the Outer Carpathian accretionary wedge nappe pile, the evolution of the Pannonian back-arc basin was characterized by variable tectonic styles and fault mechanisms during the Badenian (Fig. 3a,b). In the northwestern and western part a number of normal faults of NNE–SSW to NE–SW orientation were activated, at the same time bearing the character of sinistral oblique-normal slip quite often. These faults were partly connected to low angle detachment faults, which continued to accumulate large normal offsets following their Early Miocene initiation (Tari 1996).

In the southwestern part of the Pannonian Basin System, in the North Croatian Basin, the NE–SW to ENE–WSW oriented faults operated during the whole Badenian (Fig. 3a,b). Similarly the ENE–WSW oriented faults, mainly located along the broad Mid-Hungarian shear zone, gained their left-lateral strike-slip character during the latest Badenian and Sarmatian. These faults, accommodated the "elongation" of the southern Tisza-Dacia Megaunit, induced by the still active subduction in front of the Eastern Carpathian orogene (Csontos 1995; Fodor et al. 1999).

Important crustal stretching of both the Alcapa and Tisza-Dacia microplates led to structural unroofing of metamorphic core complexes by low-angle detachment faults (Tari 1996; Tari et al. 1992, 1999). The occurrences of core complexes (loci of large extension) are located in the broad transitional zone between the Eastern Alps and Pannonian Basin and ductile to brittle extension exhumed different parts of the Alpine-Carpathian nappe pile. The deepest exhumation reached the Penninic Unit in the Rechnitz window (Dunkl 1992; Tari 1994, 1996; Dunkl & Demény 1997), while shallower Austroalpine units were unroofed in the Pohorje (Fodor et al. 2002b, 2003) and in the Považský Inovec Mts (Plašienka 1995). Deep exhumation occurred in the eastern part of the Alcapa microplate, where the "Penninic type" Inatchovce-Kritchevo Unit was uplifted to the level of Miocene strata in the northern part of the Transcarpathian Basin (Soták et al. 1993). Exhumation of metamorphic rocks also associated the development of some deep syn-rift grabens below the Great Hungarian Plain (Tari et al. 1999).

Related to these extensional or transtensional structures, syn-rift subsidence continued during the Badenian in several major depocentres, including the Vienna, Danube, Styrian, Zala Basins in the West, North Croatian Basin in the Southwest, the Makó, Békés, Derecske, etc. Basins in the central and eastern part of the Pannonian Basin realm and the Transcarpathian and Transylvanian Basins in the East. The development of basins was controlled by extensional stress fields (Csontos et al. 1991; Kováč et al. 1994a,b; Fodor et al. 2002a).

In the following section we review major structures and main depositional settings for some selected sub-basins:

The northwestern, western and southwestern part of the Pannonian Basin System

During the Badenian, the **Vienna and Danube Basins** subsided in a paleostress field with NW-SE to WNW-ESE oriented extension (Fodor 1995; Tari & Horváth 1995). The crustal stretching in this direction can be estimated to range around 40 km (Tari & Horváth 1995). The basins were limited by NNE trending normal and some NE trending sinistral-normal faults (Fig. 3a,b). The thickness of the Badenian syn-rift deposits attains 1000–1500 m in both basins (Horváth 1995; Kováč et al. 1997b; Eliseeva et al. 2002).

In the **Vienna Basin**, the Lower Badenian deposits discordantly overlie the older Miocene strata and the pre-Neogene basement. They are represented by marine sediments of the Lower and Upper Lagenidae Zones, overlapped by the paleo Danube river delta (Matzen Sand) in the West. The nearshore facies of the NE basin margin are built up from conglomerates and sandstones (Špička 1969; Kováč et al. 1991a,b). In the South, the Early Badenian sedimentation started again discordantly with the deposition of the Aderklaa Conglomerate, indicating a braided river system similar to the Jablonica Formation in the North (Weissenbäck 1996). The offshore facies is represented by neritic calcareous clays, reaching up to 800 m in thickness (Špička 1969). In the northern Vienna Basin this tectonically controlled transgression is marked by the FAD of *Orbulina suturalis* inside the NN5 calcareous nannoplankton Zone (Andreyeva-Grigorovich et al. 2001). The overlying strata consist of 500–800 m thick neritic clays and siltstones (Špička 1969). They have been placed in the "Middle Badenian" *Spirorutilus carinatus* Zone. The marginal facies is represented by gravels, sands and variegated clays in the Northwest and West (thickness ~1000 m), at the northeastern basin margin 200–400 m thick alluvial fans and debris aprons were deposited (Vass et al. 1988a; Zlinská 1992a). Algal limestones and bioherms were formed at intrabasinal elevations (Láb elevation, see Špička 1969). The Leitha Mts in the southern Vienna Basin were completely covered by the sea allowing the growth of thick corallinacean limestone beds (Leitha Platform and marine shoals, see Schmid et al. 2001) with scattered coral carpets (Riegl & Piller 2000). Considerable sea-level fluctuations and phases of emersion of the carbonate platform are indicated by breccias, vadose silt, vadose leaching and caliche formation as described by Dullo (1983) and Schmid et al. (2001).

The Late Badenian flooding in the Vienna Basin is correlated with the FAD of the planktonic foraminiferal genus *Velapertina* and the common appearance of the benthic *Pappina neudorfensis* within the nannoplankton Zone NN6. The sedimentation of the *Bulimina-Bolivina* Zone started with transgressive facies of siliciclastics (silts, sands, conglomerates) with algal bioherms along the NE margin of the basin (Baráth et al. 1994). The offshore facies, deposited in a neritic environment, were influenced by stratification of the water column and anoxic conditions near the bottom. Mostly calcareous clays were deposited, reaching a thickness of 400–600 m (Špička 1969). The Leitha Mts were still covered by water allowing the growth of thick corallinacean limestone beds with coral carpets (Strauss et al. 2006). After a sea-level drop at the Badenian/Sarmatian boundary the Leitha Mts and their Badenian sedimentary cover became exposed and the mountain ridge became once again an island until the withdrawal of the Lake Pannon during the late Pannonian.

The opening of the **Danube Basin** (Little Hungarian Plain, Danube Lowlands) is first documented by the deposition of terrestrial and fluvial sediments in the central part of the present basin. Deposits reach a thickness of up to 500 m near Győr. These terrestrial deposits were previously thought to be of Karpatian age, however, the oldest marine deposits overlying them are related to the late Lower Badenian, that is to the Upper Lagenidae Zone with rich *Orbulina suturalis* assemblages and NN5 Zone nannofossils. Therefore, one can suspect, that these terrestrial sediments ranging from a few tens to few hundreds meters, could have rather been deposited during the earliest Badenian.

The Karpatian fluvial Ligeterdő Formation at the western margin of the basin (see Császár 1997) is paleogeographically related to the Eisenstadt–Sopron embayment of the Vienna Basin, since the s.s. Danube Basin and the Eisenstadt–Sopron embayment were separated by the elevated Mihályi-ridge during the whole Badenian. On the other hand, the Ligeterdő Formation is regarded as time-equivalent of the fluvial conglomerates and sandstones of the Karpatian–Lower Badenian Jablonica Formation in the northern part of the Danube and Vienna Basins, as well as to the Lower Badenian Aderklaa Conglomerate in Austria (Kováč et al. 1997a, 2004).

At the end of the Early Miocene, close to the Karpatian/Badenian boundary the calc-alkaline volcanism started on the northern rim of the Danube Basin. This volcanism (Rusovce, Kráľová, Šurany stratovolcanoes) was associated with the back-arc extension (Hrušecký et al. 1996) and is covered by the "Middle" to Upper Badenian basin fill.

The Lower Badenian shallow marine to neritic deposits of the Upper Lagenidae Zone are known only from the deepest parts of the southern and central Danube Basin and from the northeastern part of the basin, filling the Želiezovce Depression in front of the Transdanubian Range Mts. The transgressive, littoral conglomerates and sandstones pass towards the basin centre into neritic calcareous clays and siltstones reaching 500 m in thickness (Keith et al. 1994). The "Middle" and Upper Badenian sediments of the *Spirorutilus carinatus* and *Bulimina–Bolivina* Zones occur in the entire Danube Basin. Transgression is dated by the foraminiferal association *Praeorbulina* together with *Orbulina* inside of the nannoplankton NN5 Zone (Zlinská & Halásová 1999; Andreyeva-Grigorovich & Halásová 2000). They were deposited in a neritic environment where salinity as well as depth continuously decreased toward the end of the Late Badenian (Kováč et al. 2001). In the northwestern part of the basin, the offshore facies is represented by clays, siltstones and sandstones reaching a thickness of up to 3000 m (Adam & Dlabač 1969; Fordinál et al. 2002). In the eastern part of the basin, in the Komjatice Depression, sediments of similar facies were deposited, differing mainly in the occurrence of volcaniclastics and also including algal bioherms. The Badenian sediments are about 2000 m thick here (Nagy et al. 1998). In the main axis of the basin clayey marls were deposited in a deep marine environment. On the submerged flanks of the Transdanubian Range, at the SE basin margin, large patches of Upper Badenian algal limestones occur (Rákos Limestone, see Császár 1997). The Pásztori trachyalkaline volcano in the basin center erupted first during the Late Badenian and its activity lasted till the early Pannonian (see Császár 1997).

The southern and central parts of the **Transdanubian Range** represented the emerged edge of large tilted fault block of the southern Danube Basin (Fig. 4). However, the particularity of the internal deformation of the range is that some WNW trending dextral-transtensional faults were present and bounded some local depressions (Kókay 1966, 1976; Mészáros 1982). Badenian sediment thickness is small and sedimentation occurred only in confined small depressions and along the rim of the range (Selmeczi 1989; Dudko et al. 1992; Budai et al. 1999). The shallow marine sedimentation was often mixed with deltaic to terrestrial deposition.

The tectonic evolution of the **Styrian Basin** situated in the foothills of the Eastern Alps can be characterized by termination of the Early Miocene synrift phase during the so-called "Styrian Tectonic Phase". This event led to a shallowing and finally to tilting of the upper Karpatian sediments. In marginal areas considerable erosion took place and the Badenian deposits are separated by a distinct angular unconformity. The andesitic and shoshonitic volcanism of the Styrian Basin continued from the Karpatian up the Early Badenian (Ebner & Sachsenhofer 1991).

The Early Badenian marine ingression started already in the late NN4 Zone of calcareous nannoplankton, with the occurrence of *Praeorbulina sicana*, followed by a major

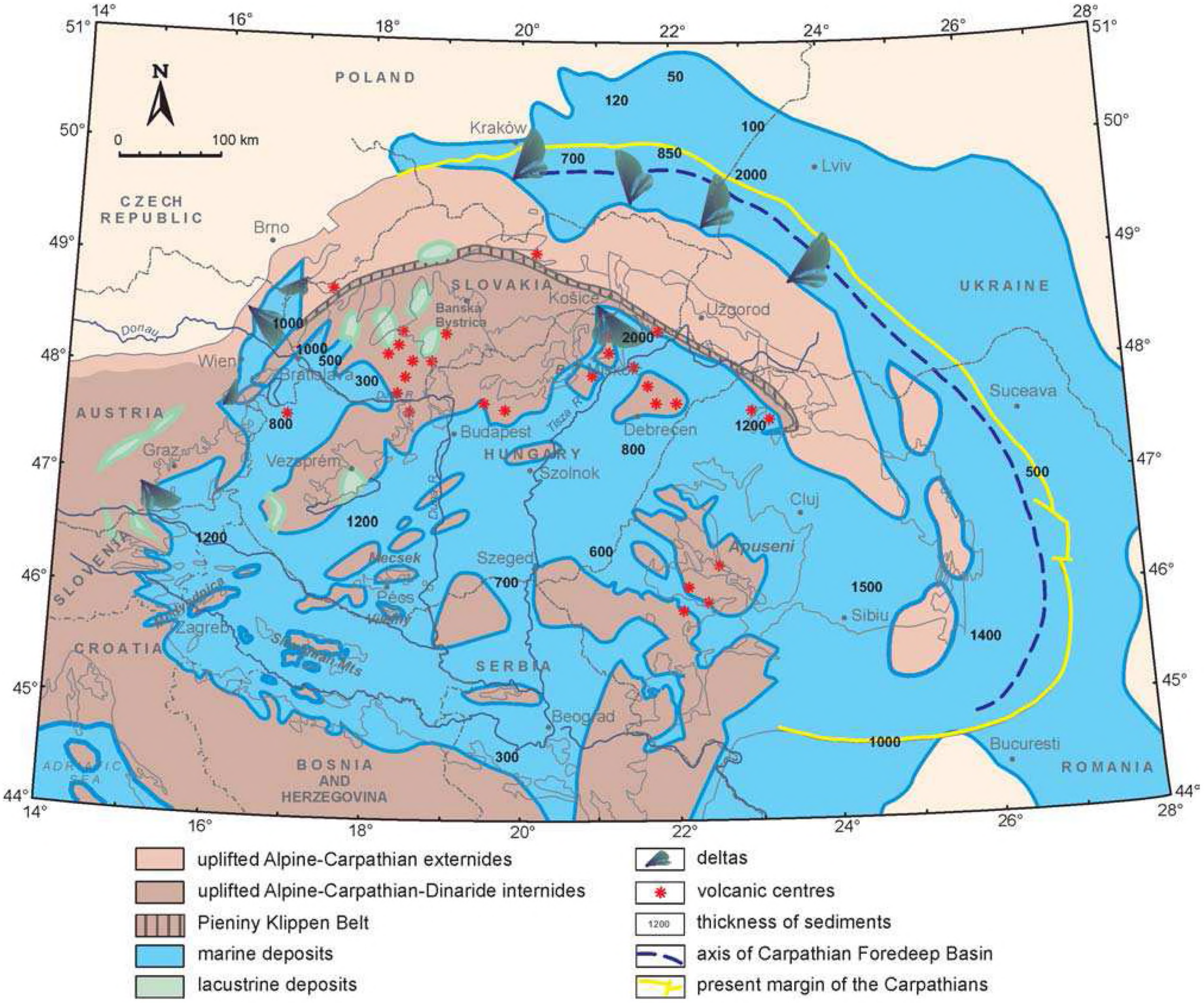


Fig. 4. Paleogeographical-palinspastic map of the Central Paratethys during the Late Badenian (early Serravallian–Late Badenian–Konkian (13.6–12.7 Ma)).

transgression event within NN5 and the co-occurrence of *P. glomerosa circularis* (Rögl et al. 2002). These transgressions led to the establishment of shallow marine conditions with widespread patch-reefs and corallinacean limestones along shorelines and swells (Friebe 1990). Sublittoral to fairly deep water marly and pelitic sediments were deposited in the basin and graben structures (Spezzaferri et al. 2004). The Badenian sediment thickness in the subbasins varies from a few hundred meters to about 750 m in general (Kollmann 1965). In deep structures, such as the deep-well Perbersdorf-1, the Badenian marine sediments attain a thickness of more than 1300 m, and a Badenian basal conglomerate of variable thickness. A major drop of the relative sea level occurred at the Badenian/Sarmatian boundary (Sachsenhofer et al. 1996).

The **Fohnsdorf Basin** and **Lavanttal Basin** formed West, Northwest of the Styrian Basin at a junction of two strike-slip fault systems (Sachsenhofer et al. 2000; Strauss et al. 2003). These fault systems, the sinistral ENE-WSW trending Mur-Mürz-Fault System and the dextral NNW-SSE trending Pöls-Lavanttal-Fault System form the border of the escaping crustal wedge which hosts the Styrian Basin (Figs. 3a, 4). During the Badenian, the Fohnsdorf Basin experienced a half-graben stage and was covered by flood plain and lacustrine fan delta environments. These immature conglomerates and sandstones were united in the Apfelberg Formation by Straus et al. (2003). The Lavanttal Basin situated west of the Styrian Basin, is a pull-apart basin between the crystalline of the Saualpe and Koralpe. Sedimentation started with Karpatian continental beds. At the Early/Middle Miocene boundary the basin geometry changed considerably due to the activation of the Pöls-Lavanttal-Fault System resulting in a 27 km long NNW-SSE trending basin. Consequently, the Lower Badenian is separated by an unconformity. Diverse mollusc and foraminiferal fauna derived from the marls of the Lower Badenian indicate a marine ingression. This short-lived connection to the Paratethys ceased during the Middle and Late Badenian when fluvial-lacustrine environments became installed, but was rejuvenated during the Lower Sarmatian.

In the Southwest, extension also controlled subsidence in the **Mura-Zala Basin**, where, near Budafa, the Badenian marine deposits are up to 1000 m thick (Horváth 1995). The Early Badenian deformation of the basin was marked by ENE-WSW extension (Fig. 3a,b). The presence of low-angle normal faults both in the Pohorje Mts and in the Murska Sobota High and the associated high-angle normal faults induced the formation of a considerable thickness of more than 500 meters. The high-angle normal faults propagated through the previously deposited thick Karpatian syn-rift sequence. The sedimentation occurred in half grabens that reached several hundreds of meters in depth (Márton et al. 2002; Jelen & Rifelj 2005). In the deep grabens deposited neritic marls often intercalated by turbidity flows, derived from the uplifted basin margins. On the other hand, carbonate build-ups have occupied the shallow marine environments, generally near fault-block edges (Kőrössy 1988; Fodor et al. 2002a). The Middle and Late Badenian are charaterized by decreasing water depth, probably due to the decrease or complete cessation of faulting.

The **North Croatian Basin (Drava and Sava Depressions)** opened in the Early Miocene along WNW-ESE faults, as elongated half-grabens with continuous alluvial, lacustrine to marine offshore sedimentation (Kováč et al. 2003). The sea-level fall at the end of the Karpatian marks the onset of uplift resulting from rotation of the fault blocks. Fault block crests were thus uplifted above the sea level and strongly eroded, and large quantities of the mostly coarse-grained syn-rift deposits were resedimented particularly in the marine shallows during the Early Badenian transgression. The uplift was contemporaneous with sinistral NE-SW strike-slip faulting (Fig. 3a,b) transverse-to-oblique to the master WNW-ESE elongated structures (Jamičić 1995; Prelogović et al. 1995). These faults disintegrated the elongated half-graben structures, and in this way reduced the effects of the uplift in some parts of the blocks, and resulted in continuous Karpatian to Badenian sedimentation (Pavelić et al. 1998; Velić et al. 2000). Contemporaneously with erosion of the uplifted blocks, intensive volcanic activity was initiated in the Early Badenian, which resulted in a large quantity of volcanic rocks a few hundred to more than a thousand meters thick in the Drava Depression and in the northwesterly-located Mura Depression. The geochemical properties of the volcanic rocks indicate partial melting of the continental crust material (Pamić et al. 1995). That volcanic activity reflects the climax of the syn-rift phase (Pavelić 2001; Pavelić et al. 2003a).

The Early Badenian transgression followed the uplift of the blocks (Pavelić et al. 1998; Saftić et al. 2003). Predominance of the eustatic sea-level rise over the tectonic uplift resulted in deepening from the newly formed shallow-water to offshore environment during a relatively short period. The Late Badenian sea-level rise, which resulted in the final flooding of all the uplifted blocks and deposition of coarse-grained clastics followed by shallow-water algal limestones, and offshore mostly fine-grained material, influenced the entire North Croatian Basin. The end of the Late Badenian is characterized by regression that caused shallowing of environments and local emersion.

In the **Mecsek Mts** area, situated at the southwestern margin of the back-arc basin system, a paleostress field with main compression in NE–SW direction was documented during the Badenian (Csontos et al. 1991).

The central part of the Pannonian Basin System

The **Western Carpathians intra-mountain depressions** inside the Western Carpathian orogene, filled with 500–1000 m thick volcano-sedimentary deposits, subsided in a paleostress field with NW-SE extension during the Badenian (Hók et al. 1995). NW-SE extension was also documented from the southern slopes of the Western Carpathians in the South Slovakia–North Hungary sedimentary area (Vass et al. 1993).

South Slovakia–North Hungary: the Novohrad-Nógrád Basin (Figs. 1, 4) is located in the hinterland of the Western Carpathian mountain chain, outlined by Transdanubian Range units from the West, by units of Bükk Mts from the East and by the Mid-Hungarian fault zone from the South (the area is also called North Hungarian Range Mts). The Miocene basin subsidence reached its maximum during the Karpatian, followed by rapid regression of the sea, uplift and erosion, synchronously with widespread calc-alkaline volcanism. The Early Badenian transgressive sediments are represented by littoral and deltaic deposits (Vass et al. 1979; Vass 2002). They consist mainly of sandstones with volcaniclastic admixture containing shallow marine fauna. Sedimentary textures (various types of cross-bedding) indicate a sedimentary environment where the deposition was controlled by the dynamics of tidal movements. Segmentation of coastline led to development of various depositional systems. Besides tidal platforms and sandy barrier complexes occurrences of deltas, lagoons and carbonate bioherms are also indicated. Regression of the sea, due to volcanic activity, is documented by presence of marine fauna in lahars, which entered the littoral environment from the volcanic slope. After calming of volcanic eruptions tuffaceous deposits containing Early Badenian marine fauna with foraminiferal association *Praeorbulina* together with *Orbulina* within the nannoplankton NN5 Zone were deposited (Vass 2002). After this episode the sea definitely regressed from the South Slovakia even during the Early Badenian. The area became dry land with contrasting vertical movements of blocks outlined by faults with NW, NNW and NE strikes (Vass 1988b). Volcanic products (andesite volcaniclastics) built up the Krupinská planina Mts and Pokoradzská tabuľa Platform.

Sub-basins within the **North Hungarian Range** are marked by a pronounced change in stress field, from NE-SW to ESE-WNW oriented tension (Csontos et al. 1991; Fodor et al. 1999). The earlier deformation resulted in the formation of NW trending and the younger in NNE trending normal faults with some ENE trending sinistral faults. Carbonate sedimentation dominated shallow marine depositional environments along tilted fault blocks and around the fringes of volcanoes (Börzsöny and Mátra Mountains). Neritic marl, siltstone or clay were deposited in deeper parts of half-grabens. The carbonate-clastic sediments were intercalated or completely replaced by different volcaniclastics and/or lava flows.

The transtensional character of the Mid-Hungarian Zone is documented by the presence of localized depressions, which might have pull-apart characteristics; probably the best example is the **Derecske Basin** (Figs. 1, 3b) that opened along left lateral strike slip faults in the northwestern part of the Great Hungarian Plain (Csontos 1995; Windhoffer et al. 2005). Similarly, the Jászság Depression can be regarded as a pull-apart basin, although its detailed seismic analysis is still not published (Fig. 1).

South of the Mid-Hungarian Zone, in the area of the **Great Hungarian Plain** the shallow sea flooded pre-Neogene basement built up by the Tisza microplate units. Badenian crustal extension contributed to exhumation of metamorphic rocks below the Great Hungarian Plain (Tari et al. 1999). The low-angle detachment faults were connected to high-angle normal faults and permitted subsidence in some large grabens (Figs. 1, 3a,b). Grabens were asymmetric and had major boundary faults with changing polarity across the graben system (Györfi & Csontos 1994). Some of the grabens extended into the **Apuseni Mts** area and have actual surface expression (Györfi et al. 1999). The grabens were connected with strike-slip faults, which played the role of transfer faults accommodating differential extension near normal fault tips.

Two major depressions of the Great Hungarian Plain (Eastern Hungary), the **Békés Basin** and the **Makó Trough** seem to be formed due to low-angle detachment fault activity. All these basins show a quite uniform stratigraphical built-up during the Badenian (Császár 1997). The series starts with a few 10 to 100 meters of terrestrial deposits determined traditionally as Karpatian in age, but which very probably belong to the Early Badenian similarly to the situation in the Danube Basin. Sediments belonging to the Upper Lagenidae Zone (late Early Badenian with the planktonic foraminiferal genus *Orbulina*) are represented by transgressive conglomerates and sandstones and are overlain by the pelitic, offshore clays. Both series are interbedded with frequent tuffitic intercalations. While the time-span of sedimentation covers the "Middle" and Late Badenian as well, the amount of coarse terrigenous input diminished upwards in these basins due to the growing extension of the sea. During the Late Badenian this part of the Pannonian Basin System was an archipelago, it might have looked rather similar to the recent Aegean Sea. As a consequence of the lack of coarse terrigenous material, on the shallow sub-littoral ramps algal limestones were deposited as well as rare small reef-complexes during the "Middle" and Late Badenian.

The supposed thickness of the Badenian marly sedimentary pile in the axis of grabens exceeds 1000 m (based on geophysical data). However revision of the deepest Hungarian well Hód 1 in the Makó Trough does not confirm this and the whole sequence penetrated here documents only the Pannonian age of the sedimentary fill (Szuromi-Korecz et al. 2004), the Badenian beds should be well below this. The Pannonian sediments often contain in the lower part of the drilling redeposited Badenian fauna, also recorded from the graben margins. These margins were covered barely by thin clastic to carbonatic sediments during the Badenian.

In contrast to these deep depressions or sub basins (Derecske — 4000 m, Jászság — 3000 m, Békés — 5000 m, Makó — 7000 m of Neogene fill) some parts of the Great Hungarian Plain were flooded by shallow sea or they remained in an elevated position. The Badenian subsidence was moderate here, similarly to the Sarmatian one when erosion is also reported from many places (Horváth 1993; Meulenkamp et al. 1996). This fact can be connected with the asthenospheric mantle upheaval followed by general uplift of the back-arc basin center (Fig. 2), and associated with subsidence in its marginal parts (depocentres e.g. Danube, Drava and Sava Basins, Makó Trough, Békés and Nyírség Basins). In contrast to this trend, in some parts of central Hungary, for example in the Budapest region, the basin subsidence started only in the "Middle" Badenian and only a few 100 meters of sediments were deposited during the Late Badenian in this area.

A major depression in NE Hungary, the **Nyírség Basin** was filled up mostly by volcanic rocks whose amount increased upwards during the Badenian and Sarmatian (Szabó et al. 1992; Pécskay et al., in print). This basin mirrors the development of the eastern part of the Pannonian Basin.

The eastern part of the Pannonian Basin System

Transcarpathian and Transylvanian Basins

The **Transcarpathian Depression** (East Slovak, Solotvino and Mukachevo Basins) developed on the eastern part of the Alcapa microplate on a basement consisting of the Western and Eastern Carpathian units (Fig. 1). Paleostress field changes are connected with the development of the Outer Carpathian accretionary wedge, as well as deformations in the back-arc location. The paleostress field can be characterized at first by NE–SW extension, which changed to NW–SE extension during the Late Badenian (Vass et al. 1988b; Kováč M. et al. 1994, 1995; Kováč P. et al. 1994). It is important to note, that due to rapid subsidence more than 2000 m of deltaic to shallow marine sediments were deposited during the Late Badenian (Vass & Čverčko 1985).

The **East Slovak Basin** is situated in the NE part of the Transcarpathian Depression. The Lower Badenian sedimentation in the central and eastern part of the basin is represented by marine volcano-sedimentary deposits reaching a thickness of 500–600 m (Vass & Čverčko 1985). Along the western margin of the basin the Karpatian offshore clays pass into the Lower Badenian clays and silts, containing rich redepositions of the Karpatian microfauna in its basal part (Karoli & Zlinská 1988; Kaličiak et al. 1991, 1992). The sedimentation continued into the

"Middle" Badenian. In the central part of the basin, silts, clays and sandstones with sporadic tuff and tuffitic layers reach a thickness of 500–600 m (Vass & Čverčko 1985). The sandy material was transported from the NE, derived from the Outer Carpathians accretionary complex. The sedimentary environment of the East Slovak Basin continuously changed from deep- to shallow water (Zlinská 1992b) and finally is characterized by deposition of lagoonal evaporites of the Zbudza Formation (Karoli 1993).

The Late Badenian transgression reached the East Slovak Basin from the South. The basin formation in this time was accompanied by a wide delta system development, entering the basin from the NW. The deltaic body represents up to 1700 m thick shallow water deposits of delta platform and delta front, whose deposition also continued during the Sarmatian (Vass & Čverčko 1985). The configuration of delta lobes was controlled by syn-sedimentary tectonics, along NE–SW to ENE–WSW striking oblique normal faults (Kováč 2000). The delta plain and delta front deposits pass into offshore pelites. Dark calcareous clays, siltstones with scarce sandstone intercalations are 1000–2000 m thick in the SE part of the basin (Vass & Čverčko 1985).

In the **Transcarpathian Depression in the Ukraine**, the Lower Badenian is represented by the Tereshul Conglomerate with *Orbulina suturalis* in matrix (Venglinskij 1985); the Novoselytsa Formation and the lower part of Tereblya Formation, belonging to the NN5 Zone of calcareous nannoplankton (Andreyeva-Grigorovich et al. 1997). These deposits can be correlated with the volcano-sedimentary Lower Badenian and the "Middle" Badenian sediments in the East Slovak Basin. The Late Badenian (NN6 Zone) is represented by the upper part of the Tereblya, Solotvino and lower part of the Teresva Formations, built up mainly by calcareous clays, siltstones with scarce sandstone intercalations deposited in a neritic environment influenced by stratification of the water column and anoxic conditions near the bottom. According to nannoplankton data the upper part of the Teresva Formation belongs to the Sarmatian.

The **Transylvanian Basin** represents, in a broad sense, a post-Cenomanian sedimentary basin that developed on top of the mid-Cretaceous nappes in the eastern part of the Tisza-Dacia microplate, on Median and Inner Dacides (Săndulescu 1988). The basin's relatively thick continental crust and low surface heat flow contrasts with the thinned continental crust and high heat flow in the Pannonian Basin. While most of the intra-Carpathian basins had a typical back-arc evolution, the Transylvanian Basin's tectonic and sedimentary history was different (Krézsek & Filipescu 2005; Krézsek & Bally 2006).

The Badenian sedimentation took place in a "back-arc setting", and produced normal marine, evaporitic and volcano-sedimentary sequences, reaching thicknesses of more than 1500 m (Ciupagea et al. 1970). No extensional or salt tectonics related faults are known so far. The basin developed under a paleostress field with NE-SW or N-S oriented main compression (Ciulavu 1999; Ciulavu et al. 2000), with a high rate of subsidence between the Late Badenian and Pannonian. Several models of tectonic mechanisms, responsible for basin subsidence, were proposed (Royden 1988; Ciulavu 1999; Huismans 1999; Sanders 1999). Wide connections with the other Paratethyan basins existed during the Badenian, but the progressive rise of the Carpathian Chain restricted times the connections towards East several times.

The Lower Badenian sedimentary formations are siliciclastic, volcano-sedimentary and carbonatic (Filipescu 2001a). The foraminiferal assemblages belong to the *Praeorbulina glomerosa, Orbulina suturalis* and Lagenidae Zones. The "Middle Badenian" transgressive event (*Globoturborotalita druryi–Globigerinopsis grilli* Zone), was followed by evaporitic conditions which generated salt deposition in the deeper areas and gypsum on the western border of the basin. The Upper Badenian (*Velapertina* Zone) is mainly siliciclastic, deposited in deep marine conditions. The asymmetric subsidence of the basin produced more accommodation space towards the Carpathians, while closer to the Apuseni Mts the basin experienced starved conditions (Krézsek & Filipescu 2005).

Volcanic tuffs (e.g. Dej Tuff), resulting from the magmatic activity related to the subduction in the Eastern Carpathians and volcanism in the Apuseni Mts, are also used as markers for lithostratigraphic correlations (Mârza & Mészáros 1991; Pécskay et al. 1995). Their chemical character changed progressively from rhyolites (Badenian) to dacites (in the Sarmatian).

Volcanic activity in the Alpine-Carpathian-Pannonian domain

The Middle Miocene development of the intra-Carpathian area was associated with voluminous Badenian volcanic activity. On the basis of spatial distribution, relation to tectonics, compositional features and assumed petrological models, the following volcanic groups were distinguished: (1) indirectly related to subduction and to asthenospheric mantle diapirism and a group (2) directly related to subduction (Lexa et al. 1993; Konečný et al. 2002).

Badenian to Sarmatian areal type (extension related) rhyolitic and andesite volcanics are known from the southwestern, northwestern, central and northeasten part of the back-arc basin region, from the Miocene fill of the Drava, Styrian and Danube Basins, Central Slovak Volcanic Field, from Visegrád-Dunazug, Börzsöny, Cserhát, Mátra, Tokaj and Slánske Mountains and from the Nyírség Basin (Szabó et al. 1992; Hrušecký et al. 1993; Lexa et al. 1993; Mattic et al. 1996; Pécskay et al. 2006). Volcanics of the same type and age are also known from boreholes, buried deeply along the Mid-Hungarian fault Zone (Zelenka et al. 2004).

The arc type (subduction related) volcanic centres in the eastern part of the Pannonian back-arc basin are situated in the hinterland of the Eastern Carpathians in the Vihorlat, Gutin, Calimani, Ghiurgeni, Harghita Mts as well as in the partly buried Zemplín-Berehovo zone and the Nyírség

Basin (Nemesi et al. 1996). The activity of these volcanisms during the Late Badenian and Early Sarmatian was related to subduction in front of the Carpathians (Lexa et al. 1993; Downes et al. 1995a) and allows estimation of the size of the down-going plate before its breakdown to 200 km length maximally (Konečný et al. 2002).

In addition the Western Carpathian andesite volcanism along the Pieniny Klippen Belt zone in Moravia (Czech Republic) in the West and in Poland in the North (Birkenmajer & Pécskay 2000; Birkenmajer et al. 2004) can be related to an extension as well as to a subduction process.

The above-mentioned facts point to very important geodynamical factors, which influenced the development and paleogeography of the Carpathian orogene and the Pannonian back-arc basin system. It was the subduction, which ended much earlier in the northern front of the Carpathians (Western Carpathians) and inhibited or caused earlier rising of the asthenospheric mantle in the western and central part of the Pannonian back-arc basin (Danube, Styrian and Drava Basins, Great Hungarian Plain, etc.) during the Badenian — that is at the same time that the subduction pull in the East was controlling the formation of the Transcarpathian and Transylvanian Basins, as well as the formation of the Eastern Carpathian accretionary wedge. The Transcarpathian Basin started to develop under the influence of the rising of the asthenospheric mantle, whereas the Transylvanian Basin does not show such features.

Paleogeography, climate, global, regional and local sea-level changes in the Central Paratethys Sea during the Badenian

The **paleogeography of the Central Paratethys** during the **Early Badenian (Langhian)** is characterized by transgressions reaching the Pannonian Basin System (including the Vienna and Transylvanian Basins) and continuing toward the Carpathian Foredeep (Fig. 5). The sea flooding from the Mediterranean via Slovenia and northern Croatia (Transtethyan Trench Corridor or Trans Dinaride Corridor, see Bistricic & Jenko 1985; Rijavec 1985) to the Styrian Basin might have led across the Vienna Basin on the West, along the Mid-Hungarian Zone in central part of the Pannonian realm and along straits in the Carpathian mountain chain, which started to emerge in this period especially in the North and Northeast. Anyhow, detailed analysis of the Badenian deposits of the Eastern Carpathians show that the mountains themselves did not exist at that time, only a minor chain of islands can be supposed, dissected by several sea-corridors enhancing the faunal migrations between the Carpathian Foredeep and back-arc basins.

The "Middle Badenian" isolation of the Carpathian Foredeep, Transcarpatian and Transylvanian Basins, situated in the eastern part of the back-arc basin domain caused a wide salinity crisis in the Central Paratethys. Thick evaporite sediments, above all table salt and gypsum were deposited (Ney et al. 1974; Săndulescu 1988). This regional sea-level fall was correlated with the global sea-level fall during the TB 2.4 cycle and in some places with the lowstand at the beginning of the TB 2.5 cycle (sensu Haq 1991; Rögl 1998; Kováč 2000; Krézsek & Filipescu 2005), and was positioned at the end of the calcareous nannoplankton NN5 Zone and the beginning of the NN6 Zone.

The new magnetostratigraphic investigation in the East Slovak Basin (Túnyi et al. 2005) allowed correlation of the "Middle Badenian" salt deposits of the Zbudza Formation with the magnetic time-scale (Berggren et al. 1995). The most probable variant of correlation suggests, that the formation is coeval with Chrons C5ADr p.p., C5ADn, C5ACr, C5ACn, C5ABr, C5ABn and its numerical age is 14.7–13.3 Ma. The duration of the salinity crisis of around 1.4 million years in the East Slovak Basin seems to be very long (principally covering the whole TB 2.4 cycle time interval) and does not fit with the results of biostratigraphy, because the salt deposits are situated between agglutinated foraminiferal *Spirorutilus carinatus* or *Globoturborotalita druryi–Globigerinopsis grilli* Zones upper part and the lower part of the *Bulimina–Bolivina* Zone.

The **Late Badenian (early Serravallian)** is a short time interval but very important from a paleogeographical point of view for the Central Paratethys. It represents the latest full marine flooding (transgression) of the whole back-arc basin (including the Vienna and Transylvanian Basins), a great part of the Carpathian Foredeep and a far-reaching area over the East European Platform — Podolian Massif as well (Fig. 4). The *Bulimina–Bolivina* Zone marine environment can be regarded as being affected by stress factors such as stratification of the water column and hypoxic conditions at the basin bottom in the whole Central Paratethys.

The main problem is to create a model of sea connections, because some authors consider the western Transtethyan Corridor (Trans Dinaride Corridor) to be closed at that time (Rögl & Steininger 1983; Massari 1990) and hypotheses about a connection with the Eastern Mediterranean via the southeast — perhaps the Vardar Corridor through the Axios Valley are still controversal (Rögl 1998; Studencka et al. 1998).

Andreyeva-Grigorovich & Nosovskiy (1976), Kókay (1985), Nosovskiy & Andreyeva-Grigorovich (1978), Studencka et al. (1998) and others, speculate about a short living connection between the Central and Eastern Paratethys basins during the Late Badenian (early Konkian), when the Eastern Paratethys gained an input of marine faunal elements living in normal salinity conditions (Nevesskaya et al. 1986, 1987; Studencka et al. 1998), due to a sea connection through the re-opened Middle Araks Strait (see Gontsharova & Shcherba 1997) Eastern Georgia and the Caspian region towards the Eastern Mediterranean (Fig. 5). The return of the sea in the Eastern Paratethys during the Konkian led to its recolonization by marine fauna. No Chokrakian genus survived the Karaganian crisis (roughly corresponding to the "Middle Badenian" salinity crisis in the Central Paratethys). Therefore, the Konkian fauna consists predominantly of species that had survived in areas adjacent to the Eastern Paratethys, and reinvaded

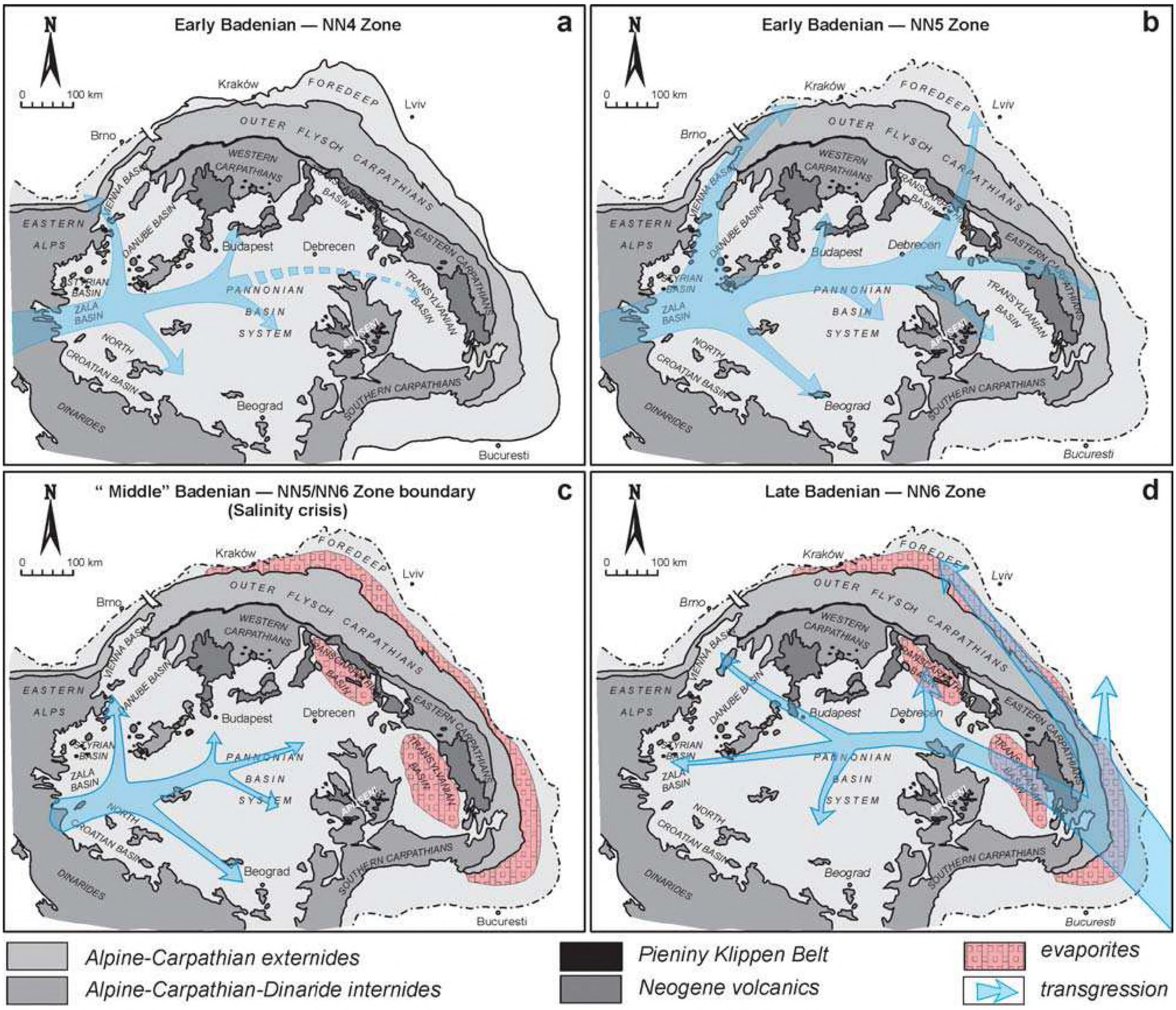


Fig. 5a,b,c,d. Central Paratethys Sea connections, migration of new marine fauna and flora (transgressions) from the Mediterranean towards the Central Paratethys area during the Badenian.

it during the Konkian transgression. The newcomers within the bivalve fauna are clearly related to faunas in the Mediterranean and Central Paratethys provinces (Studencka et al. 1998). The species restricted to the Paratethyan Province constitute more than 20 % of the Konkian fauna and they are good evidence of faunal interchange between both parts of the Paratethys during the latest Badenian (cf. Kókay 1985; Studencka et al. 1998).

This hypothesis, however, was also interpreted in opposite sense. In fact, well-documented fossil mollusc taxa prove the short, temporal connection between Central and Eastern Paratethys and the faunal exchange from Central towards Eastern Paratethys and vice versa at the very end of the Late Badenian as well (Kókay 1984).

In spite of this the Late Badenian marine fauna in the Transylvanian Basin and in the Eastern Carpathian Foredeep, as the nearest regions to the Eastern Paratethys, has an open marine character with sedimentation of radiolarites and *Spirialis* marls situated above the evaporite deposits. According to Barwicz-Piskorz (1981, 1999), the assemblages derived from the radiolarian horizon belong to the *Dorcadospyris alata* Zone in zonal scheme of Sanfilippo et al. (1985) for the Mediterranean and corresponds to the basal part of the NN6 Zone of calcareous nanoplankton (sensu Martini 1971). Distinct species of calcareous nannoplankton and radiolaria also show an affinity to the Indo-Pacific bioprovince (Dumitrică et al. 1975; Rögl & Müller 1976; Popescu 1979).

The results achieved in the Miocene **paleoceanography** of the Central Paratethys Sea corroborate an assumption that the Karpatian two-layer estuarine water circulation principially changed in the Early Badenian to an antiestuarine, Mediterranean type (Brzobohatý 1987; Báldi 2006). Instead of the Karpatian "shallow water outflow" a water regime with the principle of antiestuarine (lagoonal) circulation, with assumed "shallow water inflow" from the

Mediterranean, started during the Early Badenian. In the Late Badenian circulation possibly changed back to estuarine, with characteristic "shallow water outflow", which is well correlative with stratification of water column and hypoxic conditions near the bottom of basins. The proposed model of two-layer circulation of the Central Paratethys Sea brine fits well with climatic conditions and intensified accumulation of light marine organic matter during the Late Badenian (Báldi 2006).

The **Badenian climate of the Central Paratethys realm** can be characterized as fairly uniform and represents a part of the Miocene Climatic Optimum (Sitár & Kováčová-Slamková 1999; Böhme 2003; Slamková & Doláková 2004; Kvaček et al. 2006). The Lower Badenian sediments contain a maximum of foraminiferal genera (cf. Cicha et al. 1998; Ćorić et al. 2004) and are characterized by a highly diversified mollusc fauna and algal limestone deposition (Studencka et al. 1998; Filipescu 2001a; Harzhauser et al. 2003) reflecting a stable subtropical marine environment. The faunal associations are quite similar inside the Pannonian Basin System (from the Vienna to the Transylvanian Basin) as well as in the Carpathian Foredeep. A slight N-S gradient, however, seems to be expressed even in the Early Badenian by a maximum of thermophilic taxa (e.g. among the gastropod genus *Strombus*) in the southern basins, which are missing further to the north and northeast (Harzhauser et al. 2003), and by the decreasing diversity of some codfishes (gadoids) in a N-S direction (Brzobohatý et al., in print). In addition, the occurrence of coral build-ups is limited to the southern basins. Only one small patch reef has been recorded in the Polish Carpathian Foredeep (i.e. the northernmost part of the Central Paratethys) and its assemblage (containing four hermatypic coral taxa) is much less diversified than those of the other coral reefs occurring in the southern basins (Górka 2002). The mass occurrence of larger foraminifers *Amphistegina* and *Planostegina* characterize subtropical conditions as well, because their modern distribution is restricted by the 20 °C summer isotherms (Rögl & Brandstätter 1993).

The "Middle Badenian" *Spirorutilus carinatus* Zone (Zlinská 1993; Zlinská & Čtyroká 1993) or *Globoturborotalita druryi/Globigerinopsis* Zone (Filipescu 2001b; Krézsek & Filipescu 2005) documents a transgression and sea-level high stand conditions in a nearly identical climatic zone. The salinity crisis in eastern regions of the Central Paratethys had a different duration, and is usually related to sea regression (see Czapowski 1994; Bąbel 2004).

A cooling event in the Central Paratethys basins can be observed first in the Late Badenian marine microfauna assemblages (Dumitrică et al. 1975; Spezzaferri et al. 2004). However, the planktonic foraminiferal data (Bicchi et al. 2003) indicates a climatic cooling at the end of the Early Badenian, isochronous with an appearance of more moderate-water ostracodes (Jiříček 1983) as well as a slight increase of moderate-water gadoids (Brzobohatý et al., in print), which can be observed from the uppermost part of the Upper Lagenidae Zone.

Furthermore, a biogeographical differentiation between basins in the North and Northeast and the Pannonian back-arc basins in the South starts to become more prominent during the Late Badenian. It is characterized by absence of thermophile marine fauna in the northern Central Paratethys regions in front of the Carpathian Chain. Hence, the coral carpets and patches of the southern Vienna Basin (Riegl & Piller 2000) are contrasted by algal-vermetid buildups in the Carpathian Foredeep of Poland (Studencki 1999).

The Late Badenian coralline algal-vermetid reefs form a distinct belt along the northern and eastern margins of the Carpathian Foredeep basin, in Poland, Ukraine and Moldova. This ridge, well visible in the present-day relief in the Ukraine forming a narrow, 130-km long zone, called the Medobory Hills, separated the foredeep basin from the shallow basin over the Podolian Massif. The latter basin was slowly desalted due to increased river input and limited connection with the open sea, as shown by significant change in its molluscan fauna. In the latest Badenian the diversity of molluscs declined sharply. Rich and diversified gastropod and bivalve assemblages inhabiting sandy facies (com. Friedberg 1912–1928, 1934–1936; Studencka et al. 1998) were replaced by a few opportunistic species, which were ancestral forms to Sarmatian species.

The progress of the Late Badenian transgression produced facies uniformity within a large part of the Carpathian Foredeep. A very homogeneous complex of pelitic deposits (Machów Formation) was accumulated within an open basin at the depth of several tens of meters and in conditions of rare bottom current action. Limited water circulation and high content of suspended organic matter favoured the development of anoxic condition near the bottom (Czapowski 1994). In the lower part of this complex the mass occurrence of the holoplanktonic gastropods of the genus *Limacina* is reported. Of the nine pteropod species known from Early Badenian only one, *Limacina valvatina*, survived in the so-called *Spirialis* Beds (Janssen & Zorn 1993). It was found in greater number together with the immigrant species *Limacina gramensis* which seems to be restricted to this rather short time slice. An abundance of these two species exclusively known from the Central Paratethys and North Sea Basin indicates cold-water influence.

Decreasing surface water temperature is also inferred from less diversified planktonic foraminiferal assemblages and drastically reduced density of the warm-water planktonic foraminifers (Bicchi et al. 2003). This cooling in northern regions of the Central Paratethys is additionally confirmed by occurrence of the boreal psychrospheric ostracod genera *Cluthia* and *Pseudocythere* (Szczechura 1997). Moreover, this was the reason for the absence of warm-temperature bivalve taxa such as giant scallops *Gigantopecten* and *Flabellipecten*, cockles *Cardium indicum* (= *C. hians*), *C. kunstleri* and *Megacardita* within the Carpathian Foredeep assemblages. These taxa, commonly found in the Early Badenian assemblages of the whole Central Paratethys, were restricted during the Late Badenian only to the southern Pannonian Basin System (Studencka et al. 1998; Studencka 1999).

A slight cooling in southern regions, compared to the Early Badenian, might also be reflected by an occurrence of the *Pseudamussium lilli/scissa*-group which has a boreal origin. This pectinid-group, frequent throughout the Early Miocene in the North Sea Basin (Glibert 1945; Janssen 1984), populated the Central Paratethys in the Early Badenian (cf. Studencka & Studencki 1988) but flourished in the Late Badenian sea. It is commonly found in the Upper Badenian deposits of the fore-Carpathian basins (Poland, Ukraine and Bulgaria) whereas their records from the Pannonian back-arc basins, Transylvanian and Vienna Basins are not very frequent (Bohn-Havas et al. 1987; Studencka & Studencki 1988; Schmid et al. 2001).

Apart from slight cooling of water masses any considerable changes in the Central Paratethys terrestrial ecosystems were documented. Nevertheless, evolution of steep landscape associated with rapid uplift of the Western Carpathian mountain chain (including development of high stratovolcanoes) during this time caused development of vertical zonation of dry land and consequently close occurrence of different vegetation zones in a relatively small distance (Kvaček et al. 2006).

The **Badenian sequence stratigraphy** is both affected by global sea-level changes and regional factors, especially tectonics. We can distinguish one, two or three 3rd-order cycles of relative sea-level changes in the basins of the Central Paratethys realm (e.g. Kováč et al. 2001, 2004; Krézsek & Filipescu 2005; Strauss et al. 2006). Correlation with the global sea-level changes (sensu Haq et al. 1988; Haq 1991; Hardenbol et al. 1998) is not always easy because of the interference from the regional factors.

In the **Vienna Basin,** Kováč et al. (2004) recently proposed a threefold Badenian sequence stratigraphy, comprising three 3rd-order sequences. The Lower Badenian marine sedimentation started above a sequence boundary of SB type 1 during the Lower Lagenidae Zone marked by the appearance of *Praeorbulina*. The sediments of the neritic zone contain foraminiferal assemblages with *Lenticulina echinata* (d'Orbigny), *L. cultrata* (Montfort), *Planularia antillea ostraviensis* Vašíček, *P. dentata* Karrer, *Uvigerina macrocarinata* Papp et Turnovsky (Cicha et al. 1975; Hudáčková & Kováč 1993; Kováč & Hudáčková 1997). The "Middle Badenian" strata are deposited above a SB2 or SB1 type boundary, especially in the northern part of the basin. Agglutinated foraminiferal assemblages of the *Spirorutilus carinatus* Zone document euhaline neritic environments. Typical are *Cyclammina pleschakowi* Pishvanova, *Spirorutilus carinatus* (d'Orbigny), *Martinotiella communis* (d'Orbigny), *Textularia gramen* d'Orbigny, *Haplophragmoides vasiceki vasiceki* Cicha et Zapletalová. In some places the Upper Badenian starts with the SB2 boundary, but on SB type 1 boundary is also known from the northern and northeastern part of the basin — an excellent SB1 type boundary can be traced at the "Sandberg" locality (Švagrovský 1978, 1981; Baráth et al. 1994; Sitár & Kováčová-Slamková 1999; Sabol & Holec 2002; Sabol et al. 2004).

The sedimentary environment of the *Bulimina-Bolivina* Zone in the Vienna Basin is characterized by a stratified water column, hypoxic conditions at the basin bottom associated with deposition during sea-level high stand (Hudáčková & Kováč 1993; Kováč & Hudáčková 1997; Kováč et al. 1998). The sedimentary environment of the basins is reflected by foraminiferal assemblages of the deeper neritic zone with *Bolivina dilatata maxima* Cicha et Zapletalová, *Bulimina striata striata* d'Orbigny, *Globobulimina pyrula* (d'Orbigny), *Pappina neudorfensis* (Toula), *Globoturborotalita druryi* Akers, *Globigerinoides quadrilobatus* (d'Orbigny) and common *Globigerina bulloides/praebulloides*. In the Vienna Basin pteropod mass occurrences were also documented (Zorn 1991). Following the data above we can correlate the relative cycles of sea-level changes in the Viena Basin with cycles of the global sea-level changes **TB 2.3, TB 2.4 and TB 2.5** (sensu Haq et al. 1988; Haq 1991).

According to Friebe (1993) the Badenian of the **Styrian Basin** also falls apart into three marine sequences, which are expressions of the global "Haq"cycles **TB 2.3–2.5.**

In the **Danube Basin,** the Early Badenian transgression started from the south and reached neighbouring South Slovak–North Hungary, Novohrad-Nógrád Basin at the level characterized by the *Praeorbulina* foraminiferal assemblages, and only later by *Praeorbulina* together with *Orbulina suturalis* (Kováč et al. 1999). Taking into account the development of the basin depocentres, which shifted towards the west during the Early Badenian (in correlation with the Karpatian) and the transgressive character of the deposits we can speculate about a correlation of sediments containing *Praeorbulina* with the global sea-level change **TB 2.3** cycle (sensu Haq 1991). The Lower Badenian deposits of the Upper Lagenidae Zone are restricted beside the Novohrad Basin to the northeastern part of the northern Danube Basin — the Želiezovce Depression. Datings are based on the occurrence of *Uvigerina macrocarinata* Papp et Turnovsky and *Orbulina suturalis* Brönnimann. The sediments containing *Praeorbulina* along with *Orbulina* and calcareous nannoplankton of the NN5 Zone (sensu Martini 1971) are reminiscent of the ones in Novohrad Basin (during this time the basins were connected). The foraminiferal assemblages with a high ratio of plankton document environments of the lower neritic to shallow bathyal zone (Zlinská 1996b). The younger deposits of the *Spirorutilus carinatus* and *Bulimina-Bolivina* Zones are deposited throughout the Danube Basin. The foraminiferal assemblages are identical with those of the Vienna Basin and are equivalents of the **TB 2.4** and **TB 2.5** cycles.

In the **East Slovak Basin** the Lower Badenian deposits contain planktonic foraminiferal assemblages with *Praeorbulina glomerosa* (Blow), *Orbulina suturalis* Brönnimann, *Globigerinoides quadrilobatus* (d'Orbigny), *G. trilobus* (Reuss), documenting the neritic environment of the open sea during transgression and beginning of the high stand (Kováč & Zlinská 1998). The high stand conditions in the neritic to shallow bathyal zone is documented by agglutinated foraminiferal assemblages with *Spirorutilus* *carinatus* (d'Orbigny), *Cyclammina vulchoviensis* Venglinsky, *C. complanata* Chapman, *Globigerina praebulloides* (Blow) and *Paragloborotalia mayeri* (Cushman et Ellisor) (Zlinská 1992b, 1996a, 1998). The end of sedimentation is represented by shallow water evaporites of the Zbudza Formation (Vass & Čverčko 1985). We correlate the "Middle" Badenian evaporites in the East Slovak Basin (Kováč & Zlinská 1998) with the evaporites in the Transcarpathian and Transylvanian Basins, as well as with the Carpathian Foredeep (Rögl 1998). This event can be correlated with the sea-level fall at the end of the **TB 2.4 cycle** (sensu Haq et al. 1988; Haq 1991). The SB type 1 boundary is represented by the surface of the evaporites flooded by the offshore Upper Badenian sediments, representing transgressive and high stand deposits of the **TB 2.5 cycle** (sensu Haq et al. 1988; Haq 1991). The sedimentary environment of the *Bulimina-Bolivina* Zone in the East Slovak Basin is characterized by a stratified water column, hypoxic conditions (events) at the basin bottom similar to the conditions in the Vienna Basin (Kováč & Zlinská 1998; Kováč et al. 1998). The Upper Badenian sedimentation in the East Slovak Basin ended with hyposaline deposits containing a foraminiferal association with *Ammonia*. Moreover, the falling stage and following Sarmatian lowstand is documented by basinward progradation of the Badenian deltaic system in the NW part of the basin (Kováč et al. 1995).

In the **eastern North Croatian Basin** the end of the Karpatian is characterized by progradation, that is by rapid shallowing of the offshore environment, which graded to the Lower Badenian shoreface and Gilbert-type fan deltas (Pavelić et al. 1998). The Early Badenian is suggested by the first occurrence of the *Amphistegina mammilla* (sensu Rögl & Brandstätter 1993). The transition from rapid progradation to an aggradational parasequence stacking pattern composed of the shoreface deposits is found bounded by a SB type 2. The shoreface deposits are overlain by biocalcarenites and marls which contain foraminiferal species *Praeorbulina glomerosa* (Blow), *Globigerinoides trilobus* (Reuss), *Paragloborotalia mayeri* (Cushman et Ellisor), *Globigerina praebulloides* Blow, *Textularia mariae* d'Orbigny, *Pseudogaudryina mayeriana* (d'Orbigny) and *Uvigerina pygmoides* Papp et Turnovsky of the Lower Lagenidae Zone. This association indicates offshore deposition as a consequence of a sea-level rise, which can be correlated with the base of the **TB 2.3 cycle** (Haq 1991; Pavelić et al. 1998; Pavelić 2005).

In the **western North Croatian Basin** the end of the Karpatian is also characterized by a sea-level fall. The beginning of the Early Badenian is represented by shoreface sediments, which contain foraminifers *Praeorbulina glomerosa* (Blow), *Orbulina suturalis* (Brönnimann) and *Globigerinoides trilobus* (Reuss). The shoreface sediments are overlain by offshore sediments containing foraminiferal associations with *Globigerina diplostoma* Reuss, *G. tarchanensis* Subbotina et Chutzieva, *Globorotalia bykovae* (Aisenstat), *Globigerinoides trilobus* (Reuss) and *G. sacculifer* (Brady) of the Lower Lagenidae Zone. This succession documents sea-level rise, which may be correlated with the base of the **TB 2.3 cycle** (Haq 1991; Avanić et al. 1995; Pavelić 2005).

Evolution of the basin at the end of the Early Badenian, that is the transition to the "Middle Badenian" is not clear and is still not known whether the end of the Early Badenian is charaterized by a sea-level fall, or the Early and "Middle" Badenian represent one transgressive-regressive cycle. There are only some indications of the sea-level fall in the western part of the North Croatian Basin at the end of the "Middle Badenian" (Avanić 1997). This regression accompanied by tectonics that created a regional unconformity between the syn- and post-rift deposits, could be a consequence of the presumed seaway closure to the Mediterranean and is correlative with the global sea-level fall at the end of the **TB 2.4 cycle** (Haq 1991; Pavelić 2005).

The Upper Badenian deposits in the southern Pannonian Basin very frequently transgressively overlie the older Miocene sediments as well as the pre-Miocene basement representing the equivalent of the sea-level rise of the **TB 2.5 cycle** (sensu Haq 1991; Pavelić 2005). The succession consists almost entirely of transgressive conglomerates, which are usually overlain by shallow-water algal limestones, and deep-water marls. These marls in the western North Croatian Basin are rich in foraminifers of the *Bulimina-Bolivina* Zone, including *Bolivina dilatata* Reuss, *Bulimina elongata* d'Orbigny, *Elphidium macellum* (Fichtel et Moll) and *Cassidulina neocarinata* Thalmann (see Vrsaljko et al. 1995), *Planostegina politatesta* (Papp et Kuepper) and *Amphistegina mammilla* (Fichtel et Moll). The Upper Badenian can be determined by *Pappina neudorfensis* (Toula), *Globoturborotalita decoraperta*, *Velapertina indigena* (Łuczkowska), *Pavonitina styriaca* Schubert (see Bajraktarević & Kalac 1998). In various localities of northern Croatia, as part of the Central Paratethys, abundant characteristic calcareous nannoplankton was described (Bajraktarević 1983, 1984). The end of the Late Badenian was characterized by hypoxic events and regression, which can be correlated with the sea-level fall at the end of the **TB 2.5 cycle** (Pavelić et al. 2003b; Pavelić 2005).

According to the sequence stratigraphic data presented by Krézsek & Filipescu (2005), the Badenian deposits in the **Transylvanian Basin** cover the Lower Miocene coarse-grained fan-delta sediments representing the lowstand systems tract of the first Badenian sequence. The Early Badenian transgression initiated the carbonate and siliciclastic sedimentation in shallow ramp environments mainly in the western part of the basin. Deeper environments with turbidites and pelagic deposition are known in the central and eastern parts of the basin. Several volcanic tuff occurrences (e.g. Dej, Perşani, Mereşti, Ioneşti) also prove the intense volcanic activity.

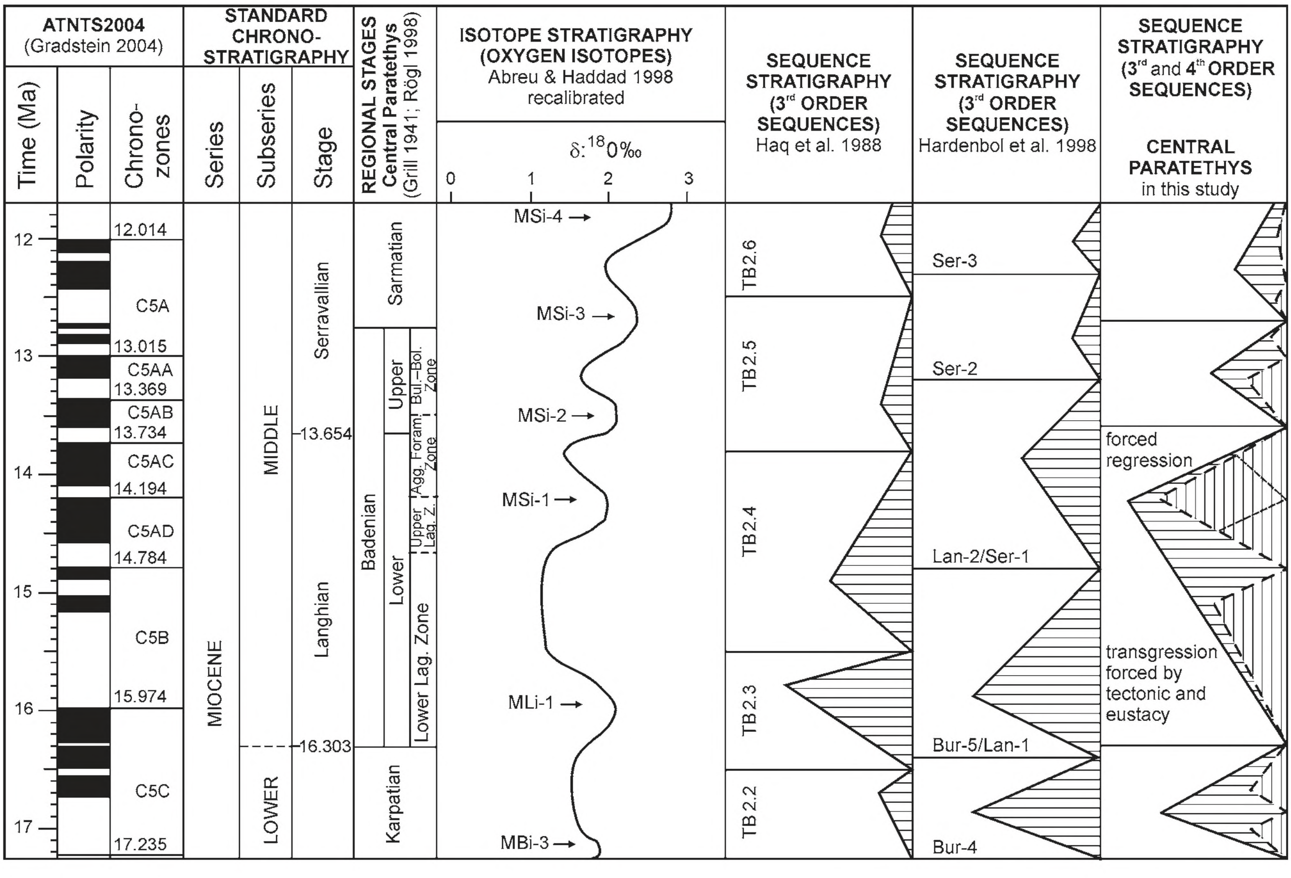
The first Badenian transgressive event can be documented by a very important planktonic bloom (*Praeorbulina glomerosa* Zone — M5a). Together with the other condensed deep-sea deposits it represents the equivalent of the **TB 2.3 cycle** of Haq et al. (1988). Deep-sea sediments also preserve the following transgressive phase, belonging to the second sequence, documented by the dominant planktonic assemblages with the *Orbulina suturalis* (M5b Zone). Benthic foraminifers progressively colonized the substrate only at the transition between the transgressive and highstand conditions, morphogroups showing affinities to offshore and shoreface siliciclastic and carbonate environments.

The uppermost facies of the Lower Badenian, mainly with carbonate sedimentation (Filipescu 2001a), indicate progressively shallower facies, ending with the lowstand conditions of the third sequence. Hemipelagic sediments above indicate an important early "Middle Badenian" transgressive event with deeper environments compared to the late Early Badenian, also suggested by the foraminiferal assemblages (*Globoturborotalita druryi–Globigerinopsis grilli* Zone). The second and third sequences in the Transylvanian Basin, generated by regional factors, are a part of the **TB 2.4 cycle** of Haq et al. (1988).

Progressive restriction of the basin circulation during the "Middle Badenian" produced the relative sea-level fall of the fourth sequence, leading to massive deposition of salt in the deep areas and gypsum at the margins of the basin. The following marine flooding event, probably associated with tectonic shortening in the Eastern Carpathians, replaced the evaporitic sedimentation with hemipelagic sediments and deep clastic turbidites with almost exclusive planktonic assemblages (*Velapertina indigena* Zone). Later, the highstand conditions induced an overall coarsening upward trend for the mid Upper Badenian stacked submarine fans. The agglutinated foraminiferal assemblages date quite precisely the progradation process (Filipescu 2004a).

Increased regional compressional stress, by the end of the Badenian, led to relative sea-level fall at the base of the fifth sequence. It generated a high sediment input, prograding shallow-marine systems and progressive restriction of the connections to the open seas. Ramp settings close to the end of the Badenian were shown by shallow marine faunas, while submarine channels were incised into the previously deposited highstand slope turbidites in the North. The transgressive trend around the Badenian/Sarmatian boundary was associated with important faunal changes (endemic *Anomalinoides dividens* acme, Filipescu 2004b), induced by the water chemistry changes in relation to paleogeographical events. Highstand conditions continued during the Early Sarmatian. The fourth and fifth sequences in the Middle Miocene deposits of the Transyl-

Table 2: Sequence stratigraphy — 3rd- and 4th-order cycles of relative sea-level changes in the Central Paratethys. *Information presented in this table/paper is compared to standard stratigraphy. The global cycles are from Haq et al. (1988) and Hardenbol et al. (1998), oxygen isotope stratigraphy was adopted after Abreu & Haddad (1998). Note that the Bur5/Lan1 boundary is adjusted following Gradstein et al. (2004). Hence, the Ser2 boundary corresponds to the Langhian/Serravallian boundary, whereas the Lan2/Ser1 boundary is positioned in the Langhian. The Ser3 boundary at 12.7 Ma is adopted due to correlation with astronomical cycles and the isotope event MSI-3 (Harzhauser & Piller 2004, 2007).*



vanian Basin are the equivalent of the **TB 2.5 cycle** of Haq et al. (1988).

Similar types of facies, sedimentary trends and cycles characterized the **Carpathian Foredeep** during the Badenian. Higher frequency of tectonic events influenced the cyclicity of sedimentation starting only with the Sarmatian (Filipescu et al. 2006).

From the sequence stratigraphy point of view, the Badenian covers the TB 2.3, TB 2.4 and TB 2.5 or Bur5/Lan1, Lan2/Ser1, and Ser2 cycles of the relative sea-level changes (sensu Haq et al. 1988; Haq 1991; Hardenbol et al. 1998; Kováč et al. 2001, 2004; Krezsek & Filipescu 2005; Strauss et al. 2006). Taking into account all bioevents, varying sedimentary record and paleogeographical changes in the area of Central Paratethys we can very roughly correlate the Early and "Middle" Badenian with the global sea-level changes of the TB 2.3 and TB 2.4 cycles and the Late Badenian with the TB 2.5 cycle (Table 2), whilst the Sarmatian already represents the TB 2.6 cycle (Harzhauser & Piller 2004).

The TB 2.3 and TB 2.4 cycle definition can state a certain discrepancy. Some authors correlate the TB 2.3 cycle duration only with the Lower Lagenidae Zone, other authors also correlate the duration of this cycle beside the Lower Lagenidae Zone with the lower part of the Upper Lagenidae Zone, or sediments assigned to the Upper Lagenidae Zone are put into the TB 2.4 cycle together with "Middle Badenian" deposits of the *Globoturborotalita druryi–Globigerinopsis grilli* Zone. This fact can be explained by tectonically controlled advance of transgression, as well as by various possibilities to distinguish the 3rd- and 4th-order cycles in most basins of the Carpathian Chain and Pannonian Basin System.

Generally, we can conclude that the Early and "Middle" Badenian transgressions were controlled by both, tectonics and eustacy (induced mainly by back-arc basin rifting) followed by forced regression. The Late Badenian transgression and regression were dominantly controlled by sea-level changes (Table 2).

Conclusions

Badenian paleogeography or the relationship between the continental environment and marine flooding of the **Alpine-Carpathian-Pannonian domain** (Fig. 4) were highly influenced by development of the orogene, above all the Outer Carpathian accretionary wedge and basin subsidence, mostly in the back-arc position. The presented model takes into consideration the configuration of the Alcapa and Tisza-Dacia microplates until their "final" juxtaposition along the Mid-Hungarian Zone (Fig. 3). The different driving forces of development (subduction pull, upheaval of asthenospheric mantle masses, stretching of overriding plates) induced different types of magmatism; extension-dominated in the western and subduction-related in the eastern Pannonian–Carpathian realm.

Subduction resulted in (1) compressional tectonics, which was bound only to the narrow belt near the collision zone and led to folding and nappe thrusting in the Outer Carpathian accretionary wedge. The load of the accretionary wedge nappe pile as well as the deep subsurface load controlled development of the Carpathian Foredeep in front of the orogen. On the other side, the subduction pull (2) resulted in stretching of overriding microplates and was accompanied by syn-rift faulting and related subsidence of separate depocentres of the Pannonian Basin System (Figs. 1, 2). In the western part of the back-arc basin the main driving force was the asthenospheric mantle uplift, following subduction in front of the Alpine–Western Carpathian Chain. In the central and eastern part of the Pannonian Basin System the basin subsidence was more directly linked to subduction pull. Therefore, NW–SE extension dominated during basin formation in the northwestern part of the Pannonian realm, W–E extension in the West, and in the southwestern part of the Pannonian realm formation of elongated half-grabens was influenced by NNE-SSW extension. Behind the active collision zone of the Eastern Carpathian Chain, in the central and eastern parts of the Pannonian Basin System the subsidence was influenced mostly by NE–SW to E–W oriented extension.

The **Central Paratethys**, covering the Pannonian Basin System and Alpine-Carpathian Foredeep represented an epicontinental sea with occasional connections with the Mediterranean and Eastern Paratethys. The first Early Badenian transgression in the Central Paratethys is documented by planktonic foraminiferal associations with *Praeorbulina sicana* and *P. glomerosa* within the NN4 calcareous nannoplankton Zone around 16.3–16.2 Ma. The sea flooding crossed Dinarides via Slovenia and northern Croatia (Transtethyan Trench Corridor) reaching the Pannonian Basin System (Fig. 5a). The second Badenian transgression is characterized by dominant planktonic assemblages with *P. circularis* and *Orbulina suturalis* in the calcareous nannoplankton NN5 Zone around 14.7 Ma. These transgressive events clearly document the stepwise flooding of the whole Pannonian Basin System. During the first transgression the sea prograded to the Styrian Basin, Alpine Molasse Basin, East and North Croatian Basin and South Slovak Basin. During the second transgressive event the sea widened to the West North Croatian Basin, Vienna Basin, Danube Basin, East Slovak Basin, Transylvanian Basin and also reached the Carpathian Foredeep (Fig. 5b). The "Middle Badenian" isolation of the eastern part of the Central Paratethys resulted in a salinity crisis in the Carpathian Foredeep, Transcarpatian and Transylvanian Basins. Thick evaporite sediments, above all table salt and gypsum were deposited (Fig. 5c). The last full marine Late Badenian transgression around 13.6–13.4 Ma covered the whole back-arc basin as well as the northern and eastern part of the Carpathian Foredeep and forereaching area over the Podolian Massif (Fig. 5d). Foraminiferal assemblages with *Velapertina indigena* and NN6 Zone calcareous nannoplankton provide evidence of it. The main problem is to create a model of sea connections during that time, because some authors consider the western "Transtethyan Trench Corridor" to be closed and there is no evidence to prove a supposed strait towards the Eastern Mediterranean. At the end of the Badenian, the final isolation of the Central Paratethys from the open seas began.

Paleoceanographical studies assume several changes of **seawater circulation pattern** in the Central Paratethys. The Karpatian estuarine circulation of water masses should have changed to an antiestuarine (Mediterranean) type of circulation at the beginning of Early Badenian. The second change is expected during the Late Badenian, when the estuarine type of circulation is expected again.

The **Badenian climate of the Central Paratethys realm** can be characterized as fairly uniform reflecting stable subtropical conditions of Mid-Miocene Climatic Optimum. Any considerable changes in the Central Paratethys terrestrial ecosystems were documented. A moderate cooling of the sea can be observed first at the end of the Early Badenian ("Middle") and during the Late Badenian. A N-S climatic gradient seems to be expressed slightly from the Early Badenian, but a biogeographic differentiation between basins in the North and South starts to become more prominent during the Late Badenian. The Late Badenian coincides with the appearance of stress factors such as stratification of the water column and hypoxic conditions at the basin bottom in the whole Central Paratethys.

The **Badenian sequence stratigraphy** is affected by global sea-level changes and by regional factors, mainly the tectonics and sediment input. We can distinguish one, two or three 3rd-order cycles of relative sea-level changes in the basins of the Central Paratethys realm. Correlation with the global sea-level changes (sensu Haq et al. 1988; Haq 1991; Hardenbol et al. 1998) is not always easy because of the interference with the regional factors. Taking into account all bioevents and paleogeographical changes in the area of the Central Paratethys we can very roughly correlate the Early (and "Middle") Badenian with the global sea-level changes of the TB 2.3 and TB 2.4 cycles. The TB 2.5 cycle can be regarded as Late Badenian. Generally, we can conclude that the Early (and "Middle") Badenian transgressions were controlled by both, tectonics and eustacy (induced mainly by back-arc basin rifting) followed by forced regression. The Late Badenian transgression and regression were dominantly controlled by sea-level changes outside the Central Paratethys realm (Table 2).

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